

PROCEEDINGS OF THE FOURTH

Natural History of the Gila Symposium

October 25–27, 2012

Western New Mexico University

Silver City, New Mexico

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Introduction

The Natural History of the Gila Symposium provides a venue for researchers, land managers, conservationists, and educators to meet and share information and ideas gathered from the Gila Region. Loosely defined, this area is situated within the watershed boundary of the upper Gila River in southwestern New Mexico and southeastern Arizona. Here, five ecoregions converge along a transition zone between the warm, dry Chihuahuan Desert and Sierra Madre Mountains of Mexico and the cool, wet Rocky Mountains of the United States. Each ecoregion contributes major floral and faunal components to make the Gila Region one of the most biologically diverse areas in North America. Elevations in this region range from 914 to almost 3,353 m (3,000–11,000 ft), with water being spatially and temporally variable. Fire plays a key role in ecosystem dynamics, as do perennial watercourses such as the Gila River, representing the lifeblood of this biologically diverse landscape to which humans have been intricately tied for millenia. Aldo Leopold, an important figure in the modern American conservation movement, first drafted the proposal to preserve the Gila Wilderness in 1922, and today 225,820 ha (558,014 acres) of wilderness lie within the 1,096,965 ha (3,324,861 acres) Gila National Forest boundary, making it the third largest National Forest in the Lower 48.

The pages that follow include the abstracts and selected papers submitted by the 37 presenters of the Fourth Natural History of the Gila Symposium, held on the campus of Western New Mexico University October 25, 2012. These proceedings open with the keynote given by U.S. Senator Tom Udall, followed by Forest Supervisor Kelly Russell's

opening remarks. Several talented nature writers were featured during the "Creative Voice" concurrent session of this symposium; we have included two of these. Peer-reviewed research presented in these proceedings includes inventories of area mosses and liverworts, an overview of the regional vertebrate fauna during the Late Cenozoic period, a classification and inventory of regional ciénegas, a summary of the Upper Gila River Fluvial Geomorphology Project, and a conservation-education initiative implemented in local fifth grade classrooms. Finally, a biography of Jack and Martha Carter provides a glimpse into the lives of two remarkable individuals whose contributions to the Gila region cannot be overstated. Martha and Jack were awarded the annual Lifetime Achievement Award by the Gila Natural History Steering Committee in recognition of their immense contributions to botanical research, education, and conservation.

We are indebted to Dr. Kelly Allred (Emeritus Professor, New Mexico State University), editor of the *New Mexico Botanist*, for facilitating publication of these proceedings as a special edition of this journal. We are grateful for the editorial assistance and reviews provided by almost two dozen people, several of whom devoted hours of their expertise to help bring manuscripts to life. We owe a special debt to Sarah Johnson, who spent many hours copyediting and formatting this publication.

—Kathy Whiteman, on behalf of steering committee members Karen Beckenbach, Joneen (Jony) Cockman, Richard Felger, William (Bill) Norris, Ted Presler, Art Telles, and Kathy Whiteman.

Welcome Address

Kelly Russell

Forest Supervisor, Gila National Forest

Good afternoon. It is great to be able to welcome all of you to this symposium and to the Gila National Forest. It did not take me very long after I arrived last year to realize what a unique resource we have here in New Mexico. This forest actually started out as the Gila River Forest Reserve in 1899, then became the Gila National Forest in 1907, so it has been a nationally recognized treasure for well over 100 years. Before that time we had the presence of the prehistoric Mimbrenos, Native American groups including the Apache, along with the Spanish and Mexican Hispanics, as well as Anglo-American settlers and ranchers, miners, and the military, all of whom offered their own contributions.

Past management decisions have helped the 3.3 million acres managed by the Gila National Forest stay relatively unchanged. These decisions include the designation of three wilderness areas, including the first designated wilderness area in the nation, the Gila Wilderness (which was designated in 1924 thanks to the efforts of Aldo Leopold), as well as the Aldo Leopold and Blue Range Wilderness Areas, for a total of over 789,000 acres. Other decisions include our fire management policies of the past several decades and the flow regimes of the Gila, San Francisco, and Mimbres Rivers, which remain primarily unrestricted by major impoundments or diversions, keeping the Gila one of the most special areas you can find in the nation.

Circumstances that have also played a role in the Gila's maintaining its uniqueness include the luck of being off the beaten path, several biotic regions coming together on this national forest (Sonoran Desert, Chihuahuan Desert, Rocky Mountains, and Sierra Madrean), and the roughness of our mountain ranges. The Mogollon, Pinos Altos, Black, and Tularosa are the larger mountain ranges on the forest. Elevations here range from 4,200 feet to almost 11,000 feet.

The result is an amazing diversity of plants, animals, and habitats on the Gila, many of which you will be hearing about over the next two days. We have some of the strongest remaining populations of several federally listed and candidate species, such as the Chiricahua leopard frog; Mexican spotted owl; southwestern willow flycatcher; native fish such as loach minnow, spikedace, Gila trout, and headwater chub; and the narrow-headed gartersnake.

There are many opportunities to enjoy the Gila National Forest; whether you are here to camp, hunt, fish, go birding, ride your OHV, visit the Cliff Dwellings or Catwalk, or have a backcountry wilderness experience, you can find it all here. We also have over 1,800 miles of trail and 33 recreation areas. You can see bear, elk, pronghorn, bighorn sheep, and mule deer, among other wildlife. Noteworthy for the birders in the group is our breeding riparian bird fauna in the Gila Valley,

which is the richest of any in the lower Colorado drainage and probably of any in the Southwest. The "Birds of the Gila National Forest" checklist documents the occurrence of 337 species of birds using the forest. I had to do a complete stop on the highway last year and turn around when I saw my first-ever sandhill crane coming in for a landing near Glenwood.

The forest is also a source for local folks with permits to get firewood, Christmas trees, and piñon each year, which are all family traditions for many people. These reasons, among others, serve to bring in tourists to the area as well as provide recreational and hunting and fishing opportunities for both visitors and locals.

One area the Gila National Forest is known for is its management of threatened and endangered species. We moved several species due to the fire this year, including narrow-headed gartersnake, spikedace, loach minnow, and Gila chub. We also removed and relocated approximately 800 Gila trout in order to get them out of the way of possible ash flows and flooding after the fire. They have been moved to other streams as well as to hatcheries to serve as future brood stock. Their future has changed but is still positive.

The Gila National Forest is also known nationally for being in the forefront of fire management—both in the wilderness and outside of it. As you know, we had a rather large fire this summer, which impacted part of the Gila Wilderness. The area is not totally burned down, as folks might think—only about 12% of the fire area was severely burned, and the area is open for visitors. This is going to be a great opportunity for us to see how an area regenerates itself—something that the Gila has been doing since long before humans arrived and that it will keep doing for a long time to come. We are sure to see a number of research papers at the next symposium on the effects of the fire.

This is the Gila. We will get more fires in the future, especially given the drought conditions we are under, the last 24 months being the driest New Mexico has had on record. Some of the fires will be more beneficial than damaging to the landscape and some will be large, fast-moving fires that may damage landscapes and threaten property. The Forest Service needs to be able to use the right tool, at the right time, and in the right place, to return the Gila to its natural fire regime while continuing to protect communities.

What will help us is management that reduces fuel in those areas most likely to have fires. Restoration of ecosystems adapted for fire is an overriding goal that we are working toward. Our approach to this is to bring in partners and see how we can best work together toward restoring these areas over a large scale.

We will continue to have projects such as thinning of

trees through timber sales and reducing fuels by conducting prescribed burns and, hopefully, through modified fire-suppression tactics. I can tell you that the Gila National Forest is prepared to deal with all of these scenarios and we plan to increase our capacity in these areas where possible.

Gila National Forest employees (approximately 200 full time and another 200 part time each year) work in everything from administration to fighting fires and improving wildlife habitat on the forest. These folks not only live here, they raise their families here and are an integral part of local communities. The Gila is a very special place to all of us and we plan to keep it that way.

While not everyone may agree with all of our management decisions, the Forest Service, with assistance from our many partners, manages the Gila National Forest for both current and future generations. We are not only looking at needs for

next year but also for 500+ years from now. It is our goal to make sure that your great-great grandchildren and beyond still have this wonderful resource to enjoy as you do today.

If you have not visited the Gila National Forest recently, then I hope you can get out and enjoy all that the forest has to offer. From mastodon bones to petroglyphs to towering canyons and scenic rivers, the Gila about has it all. I want to thank all of our partners and volunteers that continue to work so hard to keep the Gila National Forest one of the great places in New Mexico, and this is especially true for those of you who have been champions of the Gila for many years.

I know you are all waiting to hear our keynote speaker, Senator Udall, whom I would like to thank for his support for the natural resources we have on the Gila National Forest. I will turn it over to our moderator now to introduce him.

Thank you and enjoy the symposium!

Conservation: A Rich Heritage

Tom Udall

United States Senator, New Mexico

Thank you, Marcia. Thank you for that kind introduction. I am honored to be here with all of you today. I want to thank the Steering Committee for making this event possible. And thank you, President Shepard, for being our host.

I am always happy to visit this great university. And especially today. This is a terrific event. The Fourth Natural History of the Gila Symposium gathers the best and the brightest. You bring your expertise. You bring your dedication. And you are making a difference.

In his book *The Quiet Crisis*, my dad wrote:

Each generation has its own rendezvous with the land, for despite our fee titles and claims of ownership, we are all brief tenants on this planet. By choice, or by default, we will carve out a land legacy for our heirs. We can misuse the land and diminish the usefulness of resources, or we can create a world in which physical affluence and affluence of the spirit go hand in hand.

The Gila is a place we all treasure. It is rich in history. We hike its trails and follow legendary footprints. From Geronimo to Ben Lilly. From the Mogollon and Apache to Spanish explorers and prospectors in search of gold. We gaze on its amazing vistas. Places like Raw Meat Canyon and Grave Canyon. And we hear the echoes of a storied past.

In 1924, thanks to the vision of Aldo Leopold, the Gila National Forest was officially designated as a wilderness area. The first in the nation. The Gila is a pivotal chapter in the conservation movement—as my dad said, carving out a land legacy for our heirs. A way of *looking* at the world that has *changed* the world.

We honor this rich heritage. This history. But what of the future? What are the challenges we face now? That is what I want to talk about with you today.

I believe we are at a crossroads in our nation. With climate change. With scarcity of resources. With a dangerous dependence on foreign oil. But we also have great opportunities. Growing a clean energy economy. Developing renewable energy and creating jobs here at home. Pursuing what I like to call a “Do It All, Do It Right” energy policy.

So how do we make this happen? We need cooperation, not gridlock in Washington. We need to be innovative. Being at the front of the line, not in the middle of the pack—that is the true greatness of America.

One of the big concerns now is water. How to supply it. How to conserve it. We are in the worst stretch of drought in 50 years. And we are not out of it yet. Recently, I cohosted the 57th Annual New Mexico Water Conference in Las Cruces. We had a range of experts there—farmers and ranchers, academics and engineers. And other local folks. All trying to

look outside the box. Trying to figure out how to adapt and survive with drought.

It really was a time to listen. To have a discussion about an issue that is so important to the future of our state. The goal was to look for answers together. To find common ground. To think about innovative solutions.

Our farmers and ranchers have been hit hard by drought. There are things we can do right now to help them. Congress needs to pass the Farm Bill. The Farm Bill extends disaster assistance that ended in 2011 and renews other farm and nutrition programs. It passed the Senate, with my support. But the House failed to act and now the 2008 Farm Bill authorization has expired. Congress has left already-desperate farmers and families without the federal programs they depend on.

But we need long-term solutions. Not short-term fixes. The federal role is changing. In the last century, water policy was defined by big projects. Big legislation. The Hoover Dam. The Clean Water Act. Now, Washington will need to be more flexible. More collaborative. Encouraging pilot projects with newer and greener technology. Serving as a best practices clearinghouse.

Research and technology investments are crucial. And, like you, I am concerned about funding cuts. This would be short-sighted. And it would be a missed opportunity to move forward.

We also need better coordination. By one count, there are at least a dozen federal agencies with some authority over water. They all have to work together on complicated issues. So the water conference in Las Cruces was the beginning of an important conversation. And we will continue it.

Conservation efforts are more complex than ever before. Drought. Climate change. Habitat issues. Wildfires. All are great challenges. Too great to be dealt with by any single agency. Or any single group, public or private. The Department of the Interior’s new Landscape Conservation Cooperatives initiative is a step in the right direction. Through these cooperatives, agencies, businesses, and communities are identifying local conservation needs together. They are sharing their expertise. Cutting across bureaucratic boundaries. This is a model we need to see more of.

When my dad was Secretary of the Interior for Presidents Kennedy and Johnson, he had one main goal. To encourage a revival in respect for our natural resources. Working with bold leaders like Rachel Carson, Dad helped the nation welcome a new environmental perspective. He believed we were finally beginning to recover a sense of reverence for the land.

Reverence for the land. Those were not just words to my dad. They are not just words to all of you. According to Webster’s, reverence is “profound awe and respect and often love.”

My dad loved the land. And he taught me to love it as well. And to try and protect it.

This reverence, this love for the land, is crucial. It is a guiding principle of conservation. It is the reason the Gila National Forest remains a treasure for generations to enjoy. The Gila is a success story. We need more like it.

And that requires commitment. As we all know, funding is a lot harder to come by these days. There are tough choices to be made. But we have to protect our wild areas. We have to manage them wisely. And we have to be willing to pay for that. I strongly support full funding for the Collaborative Forest Landscape Program and for the Collaborative Forest Restoration Program. You are all familiar with these programs that help make our forests healthy again.

We know the fiscal realities. We have to set priorities. But one priority should be the Land and Water Conservation Fund. Since the fund was established by Congress in 1965, it has paid for recreation and conservation projects all across America. It is to be financed by offshore oil and gas revenues, \$900 million a year. But the fund has to be appropriated every year. And only a portion of the money goes where it was intended, for parks and open spaces and trails. Between 1999 and 2009, Congress allocated less than one-third of the authorized \$900 million per year to conservation and recreation.

That needs to change. Congress needs to pass the Land and Water Conservation Authorization and Funding Act of

2011. I was proud to cosponsor this bill, which was introduced by Senator Bingaman. It would authorize mandatory, full funding for the LWCF. \$900 million a year, every year.

In the meantime, the Senate version of the transportation bill would have allocated \$700 million of the fund for conservation and recreation. This would have been for 2013 and 2014. But, once again, the House chose to block. So there is work still to be done.

Conservation is not just a personal virtue. It is essential to our prosperity, to our security, and to our planet. We all know this. We know it in part because of the great conservationists who came before us, some of whom have left us. This year we lost David Henderson. David was the guiding light of the New Mexico Audubon Society.

And just last month, we lost Russell Train. Russ was a part of that great generation of bipartisan leaders—Democrats and Republicans—who put the environment center stage. Who championed conservation. My father, who knew and admired Russ, was also a part of that generation. They leave very big shoes to fill. Their legacy is inspiring. We are here today because they helped pave the way.

We honor them when we continue their work. When we protect the environment and safeguard its wonders. We owe that to this generation and to generations to come. Thank you for all that you do. I hope that you have a great meeting, and thank you again for inviting me to be with you today.

Not in Kansas Anymore: Jack & Martha Carter

Gene Jercinovic

The western half of the state of Kansas was as deeply devastated as any part of the Dust Bowl of the 1930s. The eastern half of the state certainly had its share of suffering. Jack Lee Carter was born there, in Kansas City, on January 23, 1929. A few years later the drought and winds began.

I used to go stay with my dad's parents, the Carters. Grandpa Carter was a section boss on the Santa Fe Railroad. They had a section house provided for them to live in. She had a giant tub and a washboard. She'd take all these sheets and she'd stick them in there and flush them up and down. Then, while they were still damp, she would hang them over the windows and the doors and we'd stay inside. And the dust would blow and by evening or the next morning they'd be all muddy. She'd take them down and wash them all out again.

Estel Lee and Mary Elizabeth (Zimmer) Carter had two sons, Jack and his brother Bob, four years younger. The family lived on twelve acres in Turner, Kansas, on the outskirts of Kansas City. Water came from a spring on the property. And dust wasn't the only problem.

The sky would just get dark, just almost black, and it was blacker than it was from the dust. And it was just millions and millions of great big lubber grasshoppers. And they would just come down. They'd be up there



Kansas 1934

way high and they'd just come down. They'd land on a cornfield. They would go into the cornfield and eat everything. Only the stalks would be standing.

The thirties were not easy times for the Carters. Jack's father worked for the railroad when he had the chance, but the work was irregular. He supplemented the family income by operating a second chair at the Turner barbershop. Their acreage sustained cows and chickens. A garden struggled. Like many in the Midwest during this era, the Carters' days were framed by perseverance and determination. The house had cost \$1100. The toilet was outside. Monthly payments were \$10.51.

Grandma Zimmer was giving money to Mom to help with the rent. We didn't have much. We never had a bank account. We didn't have any need for those things because we didn't have enough money coming in ever. Whatever money we had went into a brown Santa Fe Railroad envelope in the folks' room, Mom and Dad's room. It was on the right-hand side of the dresser. Dad would go down and pay the bills on payday. Whatever was left would go into the envelope and that was it for the month.

Yet hard times can provide strength and confidence to character. No one in that family felt deprived. Dreams grew.

Because he was born in January, Jack entered kindergarten four months short of his fifth birthday.

I stumbled along. I was always at the bottom of the class.

In addition to being very young, Jack had two other impediments to his early education. First, he was dyslexic. Second, he was left-handed.

For the most part, Jack enjoyed school. He was in every play. He loved music. He got along with the teachers, generally. Math was not a problem for him. Every Thursday night Jack and his mother went over the spelling words in preparation for the spelling test each Friday.

I could make an A on that, or a high grade.

His problem was reading.

It was easy for me to read from right to left. My eyes would go down to this side [right] and I would read every word backwards.

He tried to use his finger to guide his eyes, but his second-

grade teacher, Miss Bye, was sure that no one could be a competent reader using a finger and wouldn't allow it. That year did not go well. His third-grade teacher, Miss Akin, told him to put his finger anywhere he had to in order to read. He made some progress, but at the year's end Miss Akin told Jack's parents that she wished he could repeat third grade. "For my folks that was no problem." He did repeat third grade.

So finally I didn't need my finger. I just changed my eyes so that they went to the left side of the page. I went from the bottom of the class to doing great.

Jack's fourth-grade year went well for him, but not so well for his teacher, as will be discussed later. Then came fifth grade. The place of left-handedness in public education has been somewhat equivocal. In the early decades of the twentieth century it was not infrequently considered to be an abnormality. Some teachers made an issue of it. So it was with Jack's fifth-grade teacher, Miss Bell.

She got on this left-handed kick and no one was going to write with their left hand in her room. She said you can't be in the fifth grade and be left-handed. The rooms were designed so that if you write with the right hand; the windows were over there to the left. She said when you write with your left hand, you've got a shadow on your paper. It didn't bother me that much, but she made me turn my desk around and sit backwards in the room so my desk faced the cloak closet. I was the only kid in the room looking at the back.

Jack did not want his mother to find out about this since she would undoubtedly raise a considerable ruckus. However, Jack's playmate and next-door neighbor, Mary Ann Moore (yes, with red hair and freckles), told Mrs. Carter.

The very next day my mom came right down to the school and got Wallace Smith, the principal, and they went right into that room. And my mom was like crazy in that room. And they turned my desk around and the next year Miss Bell wasn't even there.

The next three years sailed quickly by. Jack adored his sixth-grade teacher, Alma Wynn, even though she made him diagram sentences.

Because she was a music teacher I just loved her and I even worked on those damn sentences.

In the seventh grade there was Mr. McMahon.

Mr. Mac was very stern, but he was wonderful.

And, as always in rural Kansas schools, the principal taught eighth grade. At the end of the eighth-grade year, students

were required to pass a state test in order to proceed to high school. With his shaky beginnings in the educational process, Jack was quite uncertain of his progress.

There was no other way and you had to get 70 on a number of these tests. I was scared. They put the fear of God in you so I thought, I'll never make it, I'm going to have to repeat the eighth grade. I did well, 85 or 90 on everything.

Jack's mother was actively involved with his schooling, very much so at home, but also with occasional trips to the school. Jack's father was also involved with the schools in Turner. Although he never actually ran for a position, he often served as an interim school board member when an elected member left the board. He felt that it was his duty to contribute as much as he could to the school system. He was not afraid of controversy. At that time only men and unmarried women were allowed to teach. Jack's fourth-grade teacher, Miss Daisy Carlin, became pregnant. The pregnancy of an unmarried woman was an extreme scandal. Without question, Miss Carlin's teaching career would have been at an end, but Jack's father "went to bat for her." He felt that she was an important asset to the school. She married and had the baby. As a result of his effort and commitment, she was actually permitted to return and resume her career. "It overthrew the old history of Kansas rural education." Of course, not all of the elder Carter's viewpoints were well received. He fought vehemently against both school lunch programs and school busing, two battles he would ultimately lose. Yet his dedication to what he believed about the educational process left a lasting impression on Jack.

In the fall of 1943, high school happened. Jack entered without any particular concern about his potential success. He had overcome earlier obstacles. He dutifully attended his classes and generally paid attention. He liked to be involved in class discussions and could ask provocative questions, but to say that he was consistent in completing assignments would be going too far. His classroom behavior was not always exemplary and he was definitely not a stranger in the principal's office. Miss Marshall, the math teacher, actually nicknamed Jack and brother Bob "Double Trouble."

Despite his moniker, Jack did well in math, but he didn't really have special interest in any one curricular area. However, he had "one hell of a science teacher." The teacher lived down the street from the Carters. Jack's parents knew him and liked him. He told the gently rebellious Jack that he had a book that might be of interest. It was Charles Darwin's *The Origin of Species*. The book had a powerful and persistent effect on Jack. As was quite typical in the forties and fifties, particularly in rural settings, church membership was very much a part of the cultural mores. In Turner there were only Catholic and Baptist churches. Jack went to Sunday school at the Baptist church. The arrival of Darwin in Jack's awareness did not bode well in that environment. Barriers were formed in his mind to numerous fundamental Christian beliefs, barriers that permeated Jack's attitudes for the rest of his life. He

could not stop himself from bringing up Darwin in Sunday school. He was never formally expelled from the class, but he was a constant problem.

For Jack, one of the most important aspects of Turner High was the athletics program. For a large fraction of students in rural Kansas, high school was the end of formal education. As a result, school activities often took on larger-than-life proportions. So it was with sports. Jack's greatest high school triumph was being a member of the Golden Bears football team. He was also on the basketball team and he ran track in spring and played summer league baseball—a sport for each season. He loved the thrill of competition and the mysterious dimension of a team beyond the simple sum of its members and, like any athlete, the interplay of defeat and victory. Excellence was essential. Unlike some other areas, in the physical domain the utmost effort and concentration were imperatives.

I was a jock.

Though far from attaining valedictory status, Jack acquired his diploma in the spring of 1946. His parents, neither of whom had graduated from high school, really wanted him to go to college. His teachers, seeing beyond his adolescence, also encouraged him to do so. Jack was not excited. Nevertheless, he convinced himself to attend Baker University in Baldwin City, Kansas, a college affiliated with the Methodist Church.

When I went to college, I didn't know what I was going to do. I thought I was going to play ball. That was a biggie.

He did well in his math classes. He made better grades in chemistry than in biology, which he



Golden Bear

thought was “kind of a bore.” Through some sort of divine miracle, he even took some Bible courses. He sang in the school choir. Going on tour with the choir around rural Kansas, staying with local families en route, was among his warmest experiences at Baker. He joined the Sigma Phi Epsilon fraternity and became a member of the football and basketball teams.

I was a freshman and a sophomore and sitting on the bench a lot for varsity basketball... playing fourth downs in football.

In his sophomore year he took organic chemistry. The professor was a sports enthusiast and went to the games. He informed Jack that he was a lot better in organic chemistry than he was in football and that if he were spending the time in chemistry that he was spending in football he wouldn't be making Cs.

That was a shocker!

Jack began to question his future as an athlete.

At Baker, those involved with biology and chemistry were considered to be pre-med students. Jack had no desire to go into medicine. He thought coaching might be a possibility. Baker just didn't seem like the right place for him, so at the end of the spring semester of 1948, he decided to drop out and go to work. That summer he hired on as a brakeman on the Santa Fe Railroad run between Kansas City and Emporia in Kansas. He intended to return to college at some point when he had refined his direction and had saved some money. The job of brakeman was less than challenging, but the pay was steady. He continued working for the railroad all summer and into the fall. In his off hours Jack played AAU (Amateur Athletic Union) basketball on a team near Turner. One of his teammates was a student at the College of Emporia. His father was “higher up in the Santa Fe Railroad.” He asked Jack why he was not in school and suggested that he should consider going to the College of Emporia. He offered to meet Jack in Emporia to help make arrangements. There he introduced Jack to the college football coach. The coach said he could get Jack a job and a place to stay. In January of 1949 Jack became a student at C of E.

His job was at a funeral home. So was his place to stay. There he shared quarters with another C of E student named John. By a remarkable quirk of fate, John had been on the football team at Baker with Jack. The two shared the work at the funeral home. Jack started as a driver, rushing flowers from the church to the gravesite. The funeral home also provided ambulance service. John didn't like going on death calls or being on call on weekends, so Jack did both and John took care of the many chores around the funeral home. Since weekend calls were few, Jack could use the on-call time to devote to his studies.

Jack's direction was now clear. He began to apply some of his athletic intensity to his academics. That year he transferred to Emporia State University and by the end of the spring semester of 1950 he had, with the exception of a single course, completed the requirements for a BS, majoring in

biological science and minoring in physical science and physical education. The state of Kansas, desperate for teachers, allowed willing individuals to teach, even short of a degree, with the option of completing the degree in ensuing summers. That fall Jack accepted a job teaching sixth- and seventh-grade math, science, and PE in Overland Park, not far from home. He also coached football and track there. Frequently he visited Turner. Now a coach himself, he often took the time to visit the high school to observe the progress of the Golden Bears.



Overland Park 1950

Martha

Martha Shelton was born on August 20, 1933, in Overland Park, Kansas. She was the first child of Richard and Gladys (McGrew) Shelton. Brother Richard, sister Barbara, and brother William followed in rapid succession. The family lived in Stony Point, a loosely knit rural area outside of Kansas City, on acreage that had once been a dairy farm. Martha's younger sister was allergic to cow's milk. As a result, the Sheltons kept a small herd of goats housed in a rock chicken house. One of Martha's first chores was to help care for the animals.

I didn't like them because I was supposed to cut grass and throw it in there. I later discovered they'll eat anything.

By the time Martha was old enough to remember, the wind and dust of the "dirty thirties" were gone. Life was not unpleasant for a young girl living in the country. There was a lot of room "to play and fool around and roam." Like other houses in the area, the Shelton house did not have city water and the toilet was outside. Water was piped into the house from a spring on the property.

So every summer we'd get this flood of boils. All our family would get these boils.

The Sheltons were not the only family to suffer from this malady. The Carters in Turner, not far away, also dealt with this seasonal problem. Years later, city water reached the area and the boils disappeared. Livestock had contaminated the springs that so many families depended on.

In the fall of 1939, Martha began school. Stony Point had

its own school for grades one through eight. It was a single building with a room for each grade. There were no indoor restrooms. Martha's family lived next door to the school. She could go home for lunch. From her parents she understood the importance of school. She would be a good student.

The minute I'd hit the back door Mother would say, "How'd you do today?"

Martha enjoyed learning. She liked her teachers and was happy to follow school and class rules. She was a good reader. Her elementary years were warm and sailed quickly by. In the eighth grade her teacher, as always, was the principal. One day she was up at his desk and looked over his shoulder. Her gaze fell on the grade book.

I saw that I was going to get a D in reading and I thought, "Oh my gosh, that's going to kill my mother."

To Martha's surprise and great relief, her mother did not depart the planet, nor did she have any particularly powerful reaction to the situation. Gladys trusted her daughter.

In the spring of 1947 Martha completed eighth grade and was ready to enter high school. There was no high school in Stony Point. Students from Stony Point went to the high school in Turner. At that time, there was no school bus service.

My mother wrung her hands for eight years about how I was going to get to high school in Turner. She had it all worked out. There was a man who went to work every day and he took kids to high school, let them off at the bottom of the hill and you'd walk up the hill and go to high school. So she had it all worked out.

This arrangement only lasted about a week. Then, despite the best efforts of Jack's father, school busing began in the county.

For Martha, high school was the place to be. She was rich with friends. Her time was full. She made sure that she would never be surprised by another D. With the exception of math, she enjoyed her classes. Not many students were motivated by the math teacher. Martha was certainly comfortable in English and history. She diligently did her biology labs. She took chemistry. In home economics she learned sewing and other domestic "practical arts." She liked secretarial training, learned shorthand, and passed the typing test. She sang in the choir.

In the fall of 1950, Martha began her senior year. By then she was thoroughly immersed in all aspects of the milieu of Turner High. That fall she went so far as to throw her hat into the ring to vie for one of the most coveted positions in any high school, Homecoming Queen. She won. She sat quietly beneath that crown, warm and fulfilled, wondering for the moment how life could get any better.

Like many others at Turner High School, she had pride in the Golden Bears football team and would even watch them practice. One afternoon later that fall she and her



Homecoming 1950

girlfriend Marlene were at the football field. Marlene was a fellow Stony Pointer who was dating a guy named Bob Carter. Martha stared down at the sideline and noticed an interesting young man beside the field.

Marlene, who's that guy?

Marlene said that it was Bob's brother, Jack.

Why don't you fix something up there?

So arrangements were made. A tradition at Turner High was a December presentation of Handel's *Messiah* before school was out for the holidays. Since Martha was a member of the choir, she would be participating. Bob was going to pick up Marlene. Jack was to pick up Martha for their first date and drive her to the performance. That day a Kansas blizzard blew in. Bob called from his job at Safeway to cancel his trip. Jack thought he should cancel his trip, but his mother and brother intervened.

Jack just came shoveling up to the door.

And Jack met Martha for the first time and delivered her to the school. Over the next several weeks they got to know each other. They realized they had much in common and just enough difference. Jack continued teaching in Overland Park. Martha still had to finish her senior year. She was having a grand time. One day her history teacher discovered that Martha was involved with Jack. The teacher advised Martha that dating Jack probably wasn't a good idea. She told Martha that when Jack left Turner High, the staff thought they were going to have to erect a statue of him in front of the principal's office since he had spent so much time there. Despite the warning, Martha thought that dating Jack was a very good idea.

Jack & Martha

On the 23rd of January, 1951, Jack received notice of his induction into the U.S. Army. After all that had happened with Martha in the few weeks preceding, this was quite a blow.

It was really terrible. I cried when I went to get on that bus. I loved those kids and teaching. But I did it. I didn't know how to be a

conscientious objector in those days. And I felt like I was leaving for prison for two years.

He was first stationed at Fort Sill in Oklahoma for basic training. Then he was off to Fort Lee in Virginia. Life in the military turned out not to be as bad as he had expected. Since he was college educated, he would not be instant cannon fodder in Korea, as would be the case for an eighteen-year-old. The army tried to channel well-educated soldiers into OCS, Officer Candidate School. To soldiers, however, OCS meant "over choppy seas." Everyone knew that the army was desperate for lieutenants to lead combat units in Korea. At Fort Lee, Jack's duty assignment was teaching classes in ABC—Atomic, Biological, and Chemical warfare. He was also assigned to a leadership course to prepare for being a second lieutenant. In the room across the hall from his classroom at the ABC facility there was a captain—a West Pointer and a fellow "Sig Ep"—teaching the same material. They became fast friends. On one weekend, they drove to Richmond to attend a party. There, Jack met a man who indicated that he had Jack's papers on his desk and asked Jack why he was going to OCS. He said that Jack was S & P (Scientific and Professional) and couldn't be sent overseas and that he could request to be assigned to his MOS (Military Occupational Specialty). All Jack had to do was sign papers to that effect, which he did the following Monday. He was assigned to Fort Lee for the duration of his service.

During the first several months of 1951, Jack kept in regular communication with Martha by writing letters. In 2011, Martha watched a television show about people losing their treasured memories in floods or fires. She decided to go through the attic and locate the things that needed keeping.

So there were the letters. (Not mine.) So I sorted them out and I still have that stuff in three boxes. So here's the "I miss you" stack and this stack said "I love you" and this stack said "Let's get married."

Jack's first furlough came in June of 1951. He had more reason than ever to head home to the Midwest. He and Martha decided that month that they were engaged. Jack discussed the matter with his parents. Jack's father just thought he was crazy. After all, Jack had brought other girls home, girls with college educations. His father just didn't think it made sense.

My folks were generally right, but sometimes they were wrong. They weren't always right. But I always said, "Okay, Mom, okay, Dad," and then I'd do what I wanted to.

For Jack, affection overwhelmed practicality.

PFC Carter returned to Virginia with a new sense of purpose. Shortly thereafter he decided that he needed to get Martha a ring.

I didn't buy many things on time, but you could buy a wedding ring and an engagement ring in a package. And I went up to

Richmond, which wasn't far—about 25 miles from Fort Lee. I just got on a bus. And I bought the package. And I paid like \$20. I didn't have much money. You paid \$20 down and \$20 a month.

Despite the fact that Martha's parents thought that she was "pretty darn young," Martha and her mother, Gladys, took a trip to Virginia in September. Jack's next furlough was in early November. They decided it would be the perfect time for Jack to make another trip back to Kansas, this time to be married. Wearing the new ring on her hand, Martha left Virginia with a quiet certainty of direction and patient excitement.

Once Martha and her mother were back in Stony Point, wedding plans were formed. Martha, together with her mother, made her wedding dress. The big day was the 10th of November. At the Stony Point Christian Church, with Jack's brother Bob as Best Man and Martha's sister Barbara as Maid of Honor, Martha became Mrs. Carter.

We were married and had a little honeymoon and then everything was packed up and Jack and I were on our way back to Fort Lee by train. As we got closer he said, "What do you think we will have as our first meal?"

Her heart sank. Her mother had always done the cooking at home, and practical arts in home economics hadn't taught cooking. But now she knew she would find a way.

Before Jack left for the wedding, he had looked into off-post housing. He had found what he considered to be quite a nice place. The rent was almost \$80 per month. Marriage would raise his monthly army salary from \$75 to \$96, but not much would be left after the rent. Nonetheless, the newlyweds moved in. Martha went out looking and quickly found another apartment for \$55 in a less upscale neighborhood.



Wedding 1951

We had to go down the hall to get to the kitchen. What's wrong with that?

She landed a job as a secretary at Firestone for \$33 a week. Their life together had begun its history.

The rest of Jack's military career was graciously uneventful. Early in 1952, Martha realized that she was pregnant. On November 1, Lizabeth Diane Carter was born at Fort Lee. By this time Jack had decided that after he got out of the army he would go back to college at Emporia State. His tour of duty was rapidly coming to an end. The army was willing to grant his release to enable him to start the spring semester, but he had one final duty. He had to march in the inaugural parade for the newly elected president, Dwight Eisenhower. One military chore that Jack had always enjoyed was close-order drill. He was assigned to a "Jody company." These were precision drill squads which, prior to the Truman presidency, had been composed of only African-American soldiers. Jack was one of a small group to be integrated into the units. Jack Carter marched in that parade—white hat, white gloves, glistening boots, the perfect soldier.

Jack's final furlough had been at Christmastime in 1952. During his holiday visit to Kansas, he had made arrangements for an apartment in Emporia. With Jack's army days safely ensconced in the past, the three Carters took up residence in Emporia and Jack began his studies in the biology department. Quite possibly the two best things about his service in the army were its completion and the GI bill. With the guarantee of 36 months of financial assistance, coupled with a graduate assistantship, the door to an advanced degree was open. That spring, in addition to several graduate courses, he completed the one course remaining from his undergraduate days and officially received his BS degree. Martha also discovered that their daughter would not be an only child.

At ESU, the graduate program in biology was designed to qualify students to teach biology in high school or junior college or to prepare them for transition to a PhD program at another university. It fit Jack's needs perfectly. He knew that he wanted to teach, but now he had a new seriousness about biological science.

I ran into a botanist there, Merle Brooks.

Jack had endured a botany course at Baker. The instructor had just read from the book. Dr. Brooks made the study of plants captivating. He introduced Jack to bacteriology. Jack also took courses in zoology, mammalogy, and limnology. Physical chemistry was a real challenge. His thesis advisor, Ted Andrews, got him involved with freshwater ecology and invertebrate zoology. As the fall semester of 1953 drew to a close, Jack was comfortably immersed in advanced biology. In the meantime, the family had grown to four with the birth of John David on November 14.

During the following spring and summer, Jack worked extensively on his field research and his thesis. He was studying the impact of the use of the pesticide and piscicide rotenone on lakes and ponds. He was also considering his options after he completed his master's. The faculty members he had come



Master's Research 1954

to know felt strongly that he should continue his education and pursue his doctorate. Dr. Andrews thought he ought to study mammalogy at the University of Michigan. Jack himself felt the greatest attraction to botany. He applied to Iowa State University, the University of Iowa, the University of Michigan, and the University of Minnesota. Ultimately he decided on the University of Iowa in order to study botany with the noted systematist and evolutionary botanist Robert Thorne. At the end of the summer Jack received his MS in biology. And Martha was carrying another child.

Jack did not attend graduation in Emporia. The Carters headed to Iowa City. Martha set up housekeeping in student housing.

They were barracks. Some people lived in Quonsets. We wouldn't have liked that. These were barracks—duplex barracks.

Jack started taking classes. He still had some GI money available and received a graduate assistantship from the university. It was enough for him to make it through the first academic year, but the prospect of several more years of graduate school was daunting, especially with a third child on the way. Laura Lee was born on April 9, 1955, at the University of Iowa hospital. It had become apparent that a major change in income was imperative.

That fall Jack accepted a job at Northwestern College in Orange City, in the northwestern corner of Iowa. The family relocated. Jack remained in the PhD program at the University of Iowa. Northwestern was a private Christian liberal arts junior college under the auspices of the Reformed Church in America (distinct from the Christian Reformed Church in America). He taught general botany, zoology, human anatomy and physiology, field botany. Northwestern was far from nonsectarian.

When I went there the first year, they had chapel in Orange City and every day they had chapel for 20 minutes, but started dropping that, while I was there, to three days a week. I didn't like leading prayer. I didn't feel good about that.

In addition, he was required to give “chapel talks.” Jack is rarely averse to talking, and was able to find things to talk about. His religious views were quite at odds with the environment, but he was careful not to make an issue of it. The Carters went to church every Sunday.

I did it out of respect for the people. I fit in with the faculty, but they knew I wasn't very religious.

He very much enjoyed his students and demanded that they study. The school administration wanted quality science instruction for the students. Topics like evolution and human reproduction were part of good science and were not restricted.

He kept the job for three years. He also coached basketball and track. On weekends he officiated basketball for extra income. Luckily, his summers were unencumbered, allowing him to do fieldwork for his dissertation on the flora of northwestern Iowa. He traveled widely in ten counties in that portion of Iowa. The Carter family transportation was a 1942 Dodge. It doubled as Jack's mobile field station.

I could sleep in the back of it. Collect plants all day. Get a six-pack of beer. Go to a state park. Drink beer and press those plants. Then get up in the morning and put the plants where I'd been sleeping.

One of his counties was Dickinson, which was home to Iowa's Great Lakes region. There were eight natural lakes in the area. The Lakeside Laboratory of the University of Iowa was located there. It was a center for research but also a place for summer courses. Jack researched the lakeshores and taught field botany there a couple of summers. Martha and the children even came up one summer and the whole family stayed in student housing. Dr. Thorne was also busy there in the summers. He and Jack got to know each other quite well. Thorne became Jack's most important mentor.

In the summer of 1958 the family left Orange City and returned to Iowa City. Jack had basically completed the fieldwork for his dissertation and he needed to begin the lengthy process of putting it into final form. To make ends meet, Jack had an assistantship and even taught extra courses for extra money. There were classes that he liked to teach and that no one else wanted to teach. Martha had been doing her part to help out.

I was supplementing by working at the university hospital at night, 11 to 7. Our neighbor was the full-time ward clerk at the hospital. I worked a few days a week at the clerk's job.

That fall, Jack and the other graduate students had to take the Graduate Record Examination in biology. Those around him were studying like crazy. Jack saw no reason for alarm. He had just been teaching general biology, as well as botany and zoology. He had familiarity with invertebrate zoology from his master's thesis. When the dust settled after the exam, it

came to light that Jack had received the highest score in the department. As a result, he received a \$2400 award from the National Science Foundation, an absolute godsend for the nearly empty Carter coffers.

Also that fall, Jack received a call from his thesis adviser, Ted Andrews, who had always maintained interest in Jack's progress. He wanted to know if Jack might be able to break away from his studies to attend a meeting of biologists who were working to improve the quality of curriculum materials in the science. After the launch of Sputnik in 1957 by the Soviet Union, the National Science Foundation established funding to revitalize instruction in science and mathematics. The School Mathematics Study Group (SMSG), the Physical Science Study Committee (PSSC), and the Biological Sciences Curriculum Study group (BSCS) were formed. Jack attended the BSCS meeting in Washington, D.C. There he saw some familiar faces from Emporia State and met the leaders of the group. He was very excited about what he saw. Ted Andrews indicated that he would put Jack's name "in the hopper" to run workshops in Iowa.

With his dissertation moving along and finances a continuing problem, in January of 1959 Jack accepted a position at Simpson College in Indianola, Iowa, about 120 miles from Iowa City. The five Carters set up shop in a third Iowa community. Simpson was another private Christian college, this time associated with the Methodist Church. Jack was hired as an associate professor of biology and settled comfortably into teaching there. Meanwhile, the University of Iowa had received an NSF grant to provide courses for high school teachers on weekends. Professors there did not want to deal with teachers (or weekends) and Jack was offered the job. He spent Monday through Friday at Simpson and traveled to Iowa City for Saturday morning classes.

I could stay with Thorne, my adviser, and make \$50, and then I'd have Saturday afternoon and Sunday to work on my research, then drive back on Sunday and teach at Simpson on Monday.

During that first semester Jack went back to Washington to attend another meeting of the BSCS group. There, BSCS advocates helped him learn the ins and outs of writing grant proposals. Back at Simpson, Jack wrote and submitted a proposal to present BSCS materials to high school teachers in Iowa and landed a grant to hold workshops during the following two summers. Subsequently, he received a grant to use BSCS curricula with high school students and submitted another proposal to the NSF, which secured several hundred thousand dollars for the purchase of new equipment for the science department. Jack had learned his lessons well.

In the spring of 1960, Jack received his PhD from the University of Iowa. His work at Simpson, as well as that at Iowa, and his involvement with BSCS had filled almost more hours than days could hold. The doctorate was a fitting and satisfying final parenthesis to his own educational experience. At this point he had become quite engaged with examining the role that teaching must play in the learning processes of

students. By 1961, the three youngest Carters were in school and Martha had decided to begin her own pursuit of a degree, enrolling there at Simpson in her first college course. She did well. Her professor remembered:

She slept with the professor. You sleep with the professor and you do well.

At other NSF meetings during his time at Simpson, Jack saw his professors from Emporia State. His successes had not gone unnoticed. The head of the chemistry department at ESU was retiring. He also headed the office in charge of research and institute grants. The university needed a qualified person who could raise money. Jack accepted the job in 1962. He was hired as an associate professor of biology. His official position was Coordinator of Institutes, but he also served as Director of Research and Institutional Grants, Associate Dean of Graduate Studies, and Assistant to the President. His responsibilities were mostly administrative. He did manage to teach one course per semester. He acted as liaison for the National Institutes of Health (NIH) and the NSF. He garnered grants to operate weekend teacher institutes all over eastern Kansas for all the NSF initiatives—BSCS, PSSC, SMSG. He was raising millions for ESU.

For Martha, the years back in Emporia were wonderful. The kids were growing up rapidly. She continued taking courses at the university. The teacher's college there even held night classes.

We were there four years. I was taking courses all along. I really liked it.

In those days in the Midwest there was no such thing as a major in education. Prospective teachers had to get a degree in a subject area. Martha was majoring in English.

In 1965 Jack received a phone call from the director of BSCS, Bill Mayer. Mayer said that he had to be in Chicago and wondered if Jack could fly in from Kansas and have dinner with him. He had some things he wanted to discuss. Jack had heard him speak at meetings and his impression of Mayer had not been the best, but he agreed to go. The BSCS group needed an associate director and Ted Andrews and others had suggested to Mayer that Jack might be the best choice. In Chicago, Jack found Mayer to be quite a reasonable fellow. Jack believed in what BSCS was trying to accomplish and felt that he could help. He would accept the position. Also that year, Jack was selected to be part of an international team, sponsored by the NSF and the University Grants Commission of India, that was to present a series of science institutes at a number of universities around that country. In his twelve weeks abroad, Jack was invigorated in ways he could never have suspected. The time was invaluable.

In 1966 Jack moved into an office in the headquarters of BSCS, a beautiful, modern building on the campus of the University of Colorado in Boulder. He was hired as an associate professor of biology at CU. However, as was the case at ESU, he was a professor in name only, managing to teach only one course per semester. BSCS dominated his time. As associate director, he found himself dealing with management

decisions and even personnel issues. He was no longer meeting with teachers or high school students. Even his botany class at CU was uncomfortable. It was held in the darkened Flatirons Theatre, which had 250 seats. Jack could imagine students sitting in the dimness "having a cigarette and reading the school paper." He began to feel that he was at an immeasurable distance from his real place in education.

Always I wanted to be in the classroom working with students and teachers, and I had to make a decision.

While Jack was plying his administrative skills and sometimes wondering about his direction, Martha was continuing her education and was the perfect hostess for evening gatherings of his colleagues. But she knew Jack was not completely satisfied with his position there and told him that she couldn't really envision herself as the wife of a university president. It was time for a change.

Jack wanted to move to a small liberal arts college and to work directly with students. Colorado College offered him a position. He visited the school and discovered separate zoology and botany departments. The two chairmen did not get along. Jack told the school that he would consider working there only if the two departments were coalesced into a single biology department. He was also looking at Evergreen State College, which was just being founded in the state of Washington. To his surprise, Colorado College eventually acceded to his request, and in the fall of 1968 Jack joined the faculty. The three Carter teenagers were relieved. They had become dedicated skiers.

Colorado College is located in Colorado Springs, which would be home for Jack and Martha for the next couple of decades. Martha completed her degree there in the spring of 1970. Teachers were in great demand, and that fall she went to work at an elementary school in Widefield, a suburb just south of Colorado Springs, where she would spend her entire career. In her first year she was hired to teach sixth grade. She found herself thrust into an experimental "open classroom" situation in which three classes were coalesced into one that was to be taught by a teacher "team" composed of Martha and two others. At the end of the semester both of her teammates resigned. Martha and two brand-new teachers had to muddle through their mutual first year. Luckily, that first year would be her last with the "open" and "team" concepts.

During Jack's first two years, Colorado College operated on a semester schedule typical of most colleges and universities, but considerable debate was occurring regarding the adoption of a "curricular block" structure. During his third year the block plan was adopted. Class sizes were limited to 24 students. The days of three one-hour lectures per week for a semester were gone. Instead, students met together with the professor all day, every day, for three and a half weeks. Both students and faculty had significant adjustments to make. Jack readily made the change. The new structure was beautiful for field courses. Jack could load up books, equipment, and students and go to Big Bend in Texas, or Bodega Bay

in California, or the Chiricahua Mountains in southeastern Arizona. He loved it.

Reunited with actual teaching and out from under the unceasing pressures of administration, Jack allowed himself to branch out a bit. From 1970 to 1974, he served as editor of the journal *The American Biology Teacher*. Though tired of executive decision making, he had never lost faith in the missions of BSCS and NSF and had continued his involvement with the groups. In 1974 he took a sabbatical leave from Colorado College to be part of an NSF project in curriculum development in Thailand. By then the Carter children were out of high school. Martha took a year's leave of absence from her job to accompany Jack on the trip. They left for Thailand in August of 1974. With war and unrest in nearby Viet Nam, Laos, and Cambodia, Thailand wasn't the safest place to be, and with Thai educators reluctant to change, Jack and Martha decided to leave in March of 1975. Even so, the trip was a great adventure and there remained for them an ease and delight in foreign travel together.

In the fall of 1975, Jack became chairman of the biology department at Colorado College. He held the position for four years. In 1977 he spent a year as president of the National Association of Biology Teachers. From 1979 to 1981, he served as consultant and writer for BSCS. In 1981 he began another sabbatical year. The All India Science Teachers Association selected Jack, as one of nine consultants from all over the world, to give a series of lectures at Indian universities. Martha took another leave of absence. Their first stop was England. Then they visited Norway, Sweden, and Denmark. Once in India, Jack was able to arrange his schedule any way he chose.

Rather than fly from stop to stop, he and Martha opted for a train pass that allowed them to experience the country. It was the trip of a lifetime. On the way home, they met daughter Laura in Hong Kong. She held a master's degree in library science and was in graduate school in Asian studies. She was on her way to China, where she had been hired to assist Chinese librarians in making use of documents newly acquired from an exchange program with the U.S. She was fluent in Chinese. Jack and Martha spent several weeks traveling around China with her and a sequence of "assigned aides." Jack knew a few professors in China from BSCS and one who had graduated from Colorado College. There



Martha in India

were some warm reunions and tales shared of the Chinese Cultural Revolution. Three Carters tasted China.

Back in Colorado in 1982, Jack began receiving calls from BSCS. Bill Mayer, who had been the director for twenty years, wanted to leave. He contacted Jack and said that he was ready for a change and wanted Jack to become director.

I didn't want to be director. I'd left there. I liked being at CC. Several board members, who were dear friends, kept calling and saying, "We need you to come," and finally three of them came to Colorado Springs. They really put the pressure on. While they were there they even contacted the president of CC.

Jack categorically refused to return to Boulder. The board countered by agreeing to sell the BSCS building in Boulder if Jack would take the money (which turned out to be 2.5 million dollars) and establish BSCS in Colorado Springs. It was an offer he couldn't refuse. Jack agreed to work half-time for BSCS and half-time at Colorado College. It was a tough go, but he served for three years.

During the second half of the eighties, CC funded a series of faculty research grants for Jack's studies of speciation in the genus *Salix*. Beginning in 1986, he began work on a book about the woody plants of Colorado.

I just put it together as I taught. I would write the keys in a three-ring notebook and bring them out with the kids and we'd test them, make changes. It was just a way of teaching.

One of his students in his beginning botany class accidentally became a major contributor to the project. She told Jack that she was interested in drawing and wondered if she could submit botanical drawings as her required five-page research paper. She showed him some examples and he readily agreed. So began a long-term connection between the two. Marjorie Leggitt produced illustrations for every species in the book, entitled *Trees and Shrubs of Colorado*, which appeared in 1988.

As the decade drew to a close, Jack began to contemplate retirement. On his numerous excursions with his students to southern Arizona, he had become familiar with the Gila Wilderness in New Mexico and the community of Silver City. He and Martha had determined that they did not want to remain in Colorado Springs and decided that Silver City would be a perfect spot for retirement. They purchased some property there.

Both retired in 1990. Martha's school district had developed an early-out program that allowed her to receive full retirement credit of 20 years despite her two leaves of absence. At CC, Jack also took advantage of an early-out program and shifted to senior status for five years at half pay (with full benefits), teaching one or two blocks per year. Jack and Martha moved into their new home in New Mexico. That

year Jack received two significant honors. He was elected a Distinguished Alumnus by Emporia State University. Also, in what he considered to be his most touching recognition, the herbarium he had worked so hard to establish at CC was officially dedicated as the Jack L. Carter Herbarium.

Jack's energy and intensity have always been phenomenal. He has been involved with the American Association for the Advancement of Science since he received a grant from the organization in 1963. He became a Fellow. He served on Section G Committee (Biological Sciences) from 1976 to 1983. He was chairman of Section Q (Education) from 1975 to 1990. His involvement on various boards and advisory groups was extensive over several decades. He was an external evaluator of biology departments at a number of colleges and universities. In his career Jack has produced more than 70 publications. After retiring, he reduced his nationwide presence but by no means turned to idleness. From 1991 to 1993, he and Martha used a research grant from CC to study woody

plants in New Mexico.

Work continued for several years, culminating in the publication of *Trees and Shrubs of New Mexico* in 1997.

The U.S. Forest Service provided funds for a number of years during the nineties and into the new millennium for field studies and herbarium materials for a database of the vascular plant flora of the Gila National Forest. His contributions to the Native Plant Society of New Mexico have been immeasurable. He has served as statewide vice president, president, and treasurer of the organization. In 2007, the



Herbarium Dedication 1990

Society established the Jack and Martha Carter Conservation Fund in their honor.

Jack estimates that over the years he has collected more than 50,000 specimens and that Martha has typed some 40,000 labels. Sheets are distributed among a number of herbaria, from Chicago and St. Louis across the Midwest to Colorado, New Mexico, and Arizona. In his Silver City years, Jack has served as mentor to a series of people interested in plants and has carried them through field and microscope into the science of botany. Jack and Martha, through their own efforts and with the help of others, produced a revised and expanded edition of *Trees and Shrubs of Colorado* in 2006. That, of course, precipitated a few more years of work to achieve a new *Trees and Shrubs of New Mexico* in 2012.



Tierra del Fuego

There was still time for a bit of travel—a Siberian journey to Lake Baikal with Russian naturalists, the tracing of some of Darwin's footsteps on the coast of Argentina, birds and plants in Costa Rica, the Panama Canal.

Martha likes to share a quaint aspect of Jack's character:

I learned that whenever Jack Carter says to me, "Do you think that you could learn to use a computer? Do you think you could learn to do to design programs? Do you think you could . . ."—watch out. You're gonna do it. The first time he ever did this was "Do you think you could learn to cook?"

Little did she know that what happened on that train going back to Virginia in 1951 would permeate her next six decades. But Jack also asked that question of himself as often as he did Martha. For both, the answer was always the same. Martha

learned how to type labels, learned how to use software to format books, learned how to create the database for the Gila National Forest, learned how to cook. Jack has always fully understood Martha's critical role.

Well, Martha made me what I am today. If there was anything good or bad, Martha was always willing to jump in.

Jack, too, in his own inimitable way, was always ready to just "jump in" and get a job done.

In their own lives, learning was a comfortable pleasure. The unraveling of mysteries and resolution of enigmas were exhilarating. Yet, for both, it was the touching of young minds that lingered in importance. The simplicity of their own beginnings brought them to the belief that the greatest responsibility of erudition is education. Both spent two decades seeking ways to reach their students. More than most, Jack and Martha have mastered that art. Jack retains a special pride in the fact that twenty-one of his students have acquired PhD's in botany.

To this day, Jack and Martha remain involved in teaching. Among other things, they assist the Gila Conservation Education Center in efforts to get school-age children in southwestern New Mexico involved in resource and environmental conservation. In 2012, they were meeting with a group of fifth graders. Martha was presenting some material to them and Jack noticed two boys in the back just talking and not paying attention.

So while she was doing her thing I got behind these two little boys and I just listened. And they were into each other. They were just talking but they were quiet, and they had a handout we had given them, leaf illustrations right out of my book. And they were saying, "I don't think that's a Goodding's willow. I think it's more like this." They weren't paying any attention because they were so into learning, and they had the best discussion going there. They had it going and I didn't want to interrupt.

Some dreams never quit growing.

A Communion With Sky

Philip Connors

New Mexico's Gila National Forest is among the most fire-prone places in America. From a lookout tower on its southern edge, I have a view over a stretch of country where an annual upsurge of moisture from the Gulf of Mexico combines with the summertime heat of the Chihuahuan Desert to create massive cumulous convection and wicked lightning shows. In an arid land with brief but intense storm activity, wildfire is no aberration. It is the forge in which the ecosystem was shaped.

Although tens if not hundreds of thousands of acres are touched by fire here every year, I can go weeks without seeing a twist of smoke. During these lulls I simply watch and wait, my eyes becoming ever more intimate with an ecological transition zone encompassing dry grasslands, piñon-juniper foothills, ponderosa parkland, and spruce-fir high country. On clear days I can see mountains in three states and two countries—the Franklins in far west Texas, the Pinalenos in eastern Arizona, and the northern reaches of the Sierra Madre Occidental in Mexico. To the east stretches the valley of the Rio Grande, cradled by the desert: austere, forbidding, dotted with creosote bushes and home to a collection of thorny species evolved to live in a land of scarce water. To the north and south, along the Black Range, a line of peaks rises and falls in timbered waves; to the west, the Rio Mimbres meanders out of the mountains. Beyond it rise more mountains—the Diablos, the Jerkies, the Mogollons—a forbidding jumble of ridges and canyons that comprise the heart of the Gila Wilderness.

Having spent a thousand days in my little glass-walled perch over the last decade, I've become acquainted with the look and feel of the country each week of each month, from April through August: the brutal gales of spring, when a roar off the desert gusts above seventy miles an hour and the occasional snow squall turns my peak white; the dawning of summer in late May, when the wind abates and the aphids hatch and ladybugs emerge in great clouds from their hibernation; the fires of June, when dry lightning connects with the hills and mesas, sparking smokes that fill the air with the sweet smell of burning pine; the tremendous storms of July, when my radio antenna sizzles like bacon on a griddle and the lightning makes me flinch as if from the threat of a punch; and the blessed indolence of August, when the meadows bloom with wildflowers and the creeks run again, the rains having turned my world a dozen different shades of green. I've seen fires burn so hot they made their own weather. I've watched deer and elk saunter through the meadow below me and pine trees explode in a blue ball of smoke. If there's a better job anywhere on the planet, I'd like to know what it is.

My office is a 7' × 7' box on stilts. Twenty paces from the cabin, sixty-five more up the steps of the tower, and just like that I'm on the job. Each April, after splitting a good stack of

firewood, cleaning up the mess left by overwintering rats and mice, and putting up the supplies I get packed in by mule, I begin more or less full-time service in the sky, 9 a.m. to 6 p.m., an hour off for lunch. My scheduled work hours are similar to those of any other jogger on the hamster wheel of the eight-hour day—except that my job involves an exquisite intimacy with wilderness, and I ply my trade inside a steel-and-glass room immaculately designed to attract lightning. It's no wonder I and my kind have been referred to as freaks on the peaks.

For most people I know, this little room would be a prison cell or a catafalque. My movements, admittedly, are limited. I can lie on the cot, sit on the stool, pace five paces before I must turn on my heel and retrace my steps. I can study once again the contours of the mountains, the sensuous shapes of the mesas' edges, the intricate drainages fingering out of the hills. On windy days in spring I turn my gaze upon the desert, a feast of eye on country if you like your country spare. In early afternoon I follow the formation of dust devils through my field glasses. Their manic life and sudden death seem to me a fruitful field of inquiry when the mind bogs down in solipsism. Far off on the desert floor, where once a great inland sea bubbled, the earth writhes up in the shape of a funnel. Scorched by sun and scoured by wind, the ancient seabed surrenders itself to points east, eventually to be washed to the Gulf in the current of the Rio Grande.

In quiet moments I devote my attentions to the local bird life. I listen for the call of the hermit thrush, one of the most gorgeous sounds in all of nature, a mellifluous warble beginning on a long, clear note. Dark-eyed juncos hop along the ground, searching for seeds among the grass and pine litter. With no one calling on the radio, I swim languidly in the waters of solitude, unwilling to rouse myself to anything but the most basic of labors. Brush teeth. Boil water for coffee. Observe clouds. The goal, if I can be said to have one, becomes to attain that state where I'm nothing but an eyeball in tune with cloud and light, a being of pure sensation. The cumulus build, the light shifts, and in an hour—or is it two?—I'm looking at country made new.

Between five and fifteen times a year I'm the first to see smoke, and once I've called it in, my superiors must choose a response. For most of the 20th century the reaction was preordained: full suppression. A military mindset prevailed in the early Forest Service, and the results for America's public lands proved disastrous. Attacking every fire the moment it was spotted warped ecosystems that had burned on a regular basis for millennia; retreating urbanites became convinced they could build their dream homes amid the forests with impunity. Smokejumpers would float out of the sky and save the day if the call came. The fact remains that wildfire has a

mind of its own, as we've learned the hard way. The lessons will only get harder in a warming world, but here in the Gila officials are committed to making fire a part of the life of the forest again. They let certain lightning-caused fires burn for weeks at a time, making the Gila healthier than it would be otherwise: more diverse in the mosaic of its flora, more open in its ponderosa savannah, with less of the brushy ladder fuels that now make the American West an almost annual show of extreme fire behavior. With crews on the ground monitoring big blazes, I keep track of crew movements and wind shifts, offer updates on fire behavior and smoke drift. I watch their weather when they sleep outside. I let them know when lightning is coming. I'm their eyes in the sky.

There were once thousands of towers scattered across America, but only a few hundred are still staffed each summer. Some in the Forest Service have predicted our impending obsolescence, thanks to better radio technology, more precise satellite imagery, perhaps even unmanned drones taking pictures on low-level fly-overs—the never-ending dreams of the techno-fetishists. But in a place like the Gila, where so much of the country is rugged and remote, off-limits to motorized equipment and new roads, lookouts are still the only communication link to the outside world for certain backcountry crews, at least for the time being. At around thirteen bucks an hour, we also remain far cheaper than aerial surveillance. Safety and fiscal prudence—these will be the saving graces of the lookouts who manage to hang on.

Aldo Leopold, who drafted the proposal to preserve the

Gila Wilderness in 1922—a plan that made the headwaters of the Gila River the first place on earth to be consciously protected from industrial machines—once wrote: “I am glad I shall never be young without wild country to be young in. Of what avail are forty freedoms without a blank spot on the map?” Survey the Lower Forty-Eight on a coast-to-coast flight, and the most interesting country never fails to be that without roads. Down there amid one of those fragments of our natural heritage is a forest that burns and a desert that dances. The view some days overwhelms me with its vastness, so I turn back to the earth beneath my feet. Wild candytuft bloom under the pine and fir, followed later in the season by wallflowers, paintbrush, mountain wood sorrel, Mexican silene. On my evening rambles I find Steller's jay and wild-turkey feathers, snake skins and mule-deer bones. Now and then an hour of hunting turns up a relic in the dirt, not far from the base of my tower: a turquoise bead or a Mogollon potsherd, white with black pattern, well more than eight hundred years old. I am given to understand the people once gathered in the high places and brought with them their crockery. They sacrificed their pots by smashing them to earth in hopes the sky gods would grant rain. Clearly I am not alone in my communion here with sky. Far from it. The ravens and the vultures have me beat by two hundred feet, the Mogollons by most of a millennium. And who's to say the dust motes off the desert don't feel joy, if only for a moment, as they climb up into sky and ride the transport winds?

Mayflies at Maytime

Sarah Johnson

I. Forever

Ephemeral, we say of this insect order: Ephemeroptera. An apt name for the mayfly adult, whose life's work might take all of a day. The aquatic mayfly nymph, however, grows fat on its stores of time: one or even two endless years. And the bulging universe: this river's shallow backwater pool whose undulating golds and greens are a dance of plenty.

Into the glow and hush steals that pulse of dissatisfaction. For what inspires a life but hunger? There is hunger for food, which the nymphs, streamlined crocodilians on six stout legs, cram into every pocket of their half-inch length. And there is hunger for oxygen, and so the skirts of their gillworks curtsy and bow. Viewed from the cobbled shore, the full company of a hundred skirted dancers can be seen at once, timed a micro-beat apart. Thus the tremolo.

They contradance and graze their pastures: drowned hulks of rock, the ooze and crumble of the pond floor, twigs and branchlets snagged by mud. They hunker down, embracing food and emulating shadows, then launch themselves, singly or in tentative galaxies (and meanwhile the constant gills flare out, essential and exact and flouncy).

The viewer, exhausted from the shimmer and the jostlings, from the charged synchronicities of mutual disregard, seeks relief in observing the stillness of mud. Those silent gashes in the soft bottom muck, those shreds of leaf-matter that are not leaves but ponderous arthropod thoughts. The current, at mysterious intervals, carries emptied mayfly skins lopsidedly past. And an underwater plume of mud unfurls to signal something's moved. A nymph, trailing its handsome tail, negotiates the maze of detritus until, at the apex of a figure-eight, it abandons this course and goes shimmying through the depths.

This is a demanding choreography, with scores and scores of everything at once. Heedless, the water rewrites it. Water is creator of the dance. But the pond has its limits. Its north-west edge is a bracket of raccoon handprints, and two meters away, along the southeast, heron tracks are laid on thick. Hunger is a restless muse. Water sucks loudly on the rocks. A mudflat cordons off the shallows from the violent river; a ragged spillway between them keeps the pond fed. But only for a time. Not even the banquet of eternity lasts forever.

II. Readiness

The universe no longer fits.

What hormonal urges hammer within the mayfly nymph? It trades the soft bed of pond-bottom muck for wind-blown towers of rock. Ascending, it slits the skin of water to enter that other, boundless universe of air.

But first, five minutes. The apparatus of the old world

must be shed. The new world has already taken shape inside, retailored a fit. Air-colored wings emerge from the coppery, water-tinted suit. A few steps and it's half in, or half out, half outmoded and half brand-new. With a little thrashing it splits itself open along its back and rears up, flush with oxygen, ready to expand into widened frontiers.

Inside-out or outside-in, the skin of its emergent body presses tight against the skin of air. It pushes away its wrinkled fishtail and steps forth with a flurry of wings like a half blast of breath, folds the wings across its new back and waits. An instant or a minute might pass before the full extent of its new tail—perhaps the most elegant touch of all—snaps free. From the finely etched abdomen, a delicate upward sweep that is optimism itself, the slender antennae-pair of the tail streams out with refinement and clarity. For a moment the tailtip might loll in the water like a lazy memory, but the mayfly will inch further skyward on the rock and squeeze that much more oblivion behind itself. The river with all that water and mud, with its jungle of debris, recedes like a cloud shooed away by a breeze. And then the mayfly leaps.

It leaps clear out of the picture. Vaporized, apparently.

(There is that leaping and then—uniquely Ephemeropteran—a second winged molt, perhaps the two-dozen-th molt since birth, and the males are swarming beside the river and the female casting herself into the thick of it to mate mid-air. And now she's back at something like her place of origin—not the shallows, to which she as a nymph migrated only recently, but the headlong river itself: there to hover, there to dip her abdomen and plant her eggs and surrender all to chance and water.)

Into the massive sky she leaps. But a titanic wind hurls her back. What short work it is to create a distant stranger. So recently at home here, now the mayfly drifts on her side, tethered to a raft of sodden wings. When a fly nips down to the water's surface to deliver torment, she's able to counter with a shiver of legs. But otherwise she has no foothold against the water's designs. She can only wash up on a lucky rock. To climb again, to squirm again, to once again muscle open those wings to the wiles of the new world's currents.

III. Rapture

Deserted garments fossilized mid-gesture. The aftermath of a mass exodus. The look of a massacre. It happened right here, the signs all say. Here, in a shallow backwater of the river, that fevered notion of the Rapture played out on the rocks. The soul—or rather, the adult mayfly—has sprung loose of its earthly package—that is to say, the trappings of the aquatic nymph—and leaped into the air. Left behind are these wingless husks, clinging with six hollow legs to the upper surface

of a stone as cratered as the moon, or paired side by side, head to tail, on a perilous cliff of cobble, or twirling in the water like a carelessly dropped wrapper.

One garment was muzzled first by water and then by a contrary wind. Another, hunched forward, seems to soldier on, a conquering ghost. Other ghosts are half submerged and half inflate at the whim of the current. There are those still vertical on the sheer sides of their islands, so near the fresh splash of water that it seems the adults could return, reoc-

cupy their costumes, and replay the drama with a different outcome.

The garments will unravel. Spiders will rustle over them. Sunlight will wear them out and wind will flick them away, exhausted memories. As the season advances, as May stumbles into the desert of June, the river will retreat from this shore and abandon the rocks to the weather. And next year the rocks will have been swept clean. They'll appear to be waiting.

A Checklist of the Liverworts of New Mexico and a Preliminary Assessment of the Liverworts of the Gila National Forest

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Abstract

In New Mexico, liverworts are less common than mosses in both abundance and diversity. We present a list of the liverworts from New Mexico that have been reported by us and others (approximately 73 species). We also report our initial findings of the liverworts that occur in the Gila National Forest (GNF), 22 taxa to date. Two taxa from the GNF are documented as new to New Mexico, *Mannia californica* and *Fossombronina* sp., the latter representing a liverwort family previously unreported in New Mexico. We are certain that more species of liverworts exist in the GNF and await discovery.

Introduction

Liverworts are also called “hepatics,” the name arising from the superficial resemblance of thalloid liverworts to the mammalian liver. In the arid Southwest, liverworts are less common than mosses, both in abundance and in number of species (in New Mexico, there are in excess of 300 species of mosses [Allred 2011]). The identification of liverworts can be challenging. For many species, reproductive structures are required for identification, and these reproductive structures are often short lived and not commonly observed. No up-to-date list of liverworts from New Mexico exists; the most recent lists, by Alan Whittemore (1995) and Richard Worthington (2001), are unpublished.

There are three basic morphologies of liverworts: complex thalloid, simple thalloid, and leafy. General characteristics of each are described below (Hicks 1992; Schofield 1985; Vanderpooten and Goffinet 2009).

Complex thalloid liverworts (Fig. 1) have thick fleshy thalli whose cross sections show differentiated layers with air pores. Complex thalloid liverworts are generally drought tolerant (Schuster 1992, p. 18).

In simple thalloid liverworts, the thallus is undifferentiated and sometimes only one cell thick. Simple thalloid liverworts are very uncommon in New Mexico (see Table 1).

Leafy liverworts superficially resemble mosses (Figs. 2 and 3), but can be distinguished by microscopic examination. Leaves of leafy liverworts virtually never have a costa (mid-vein); costae are found in a majority of mosses. Liverwort leaves often have multiple lobes; this characteristic is rare

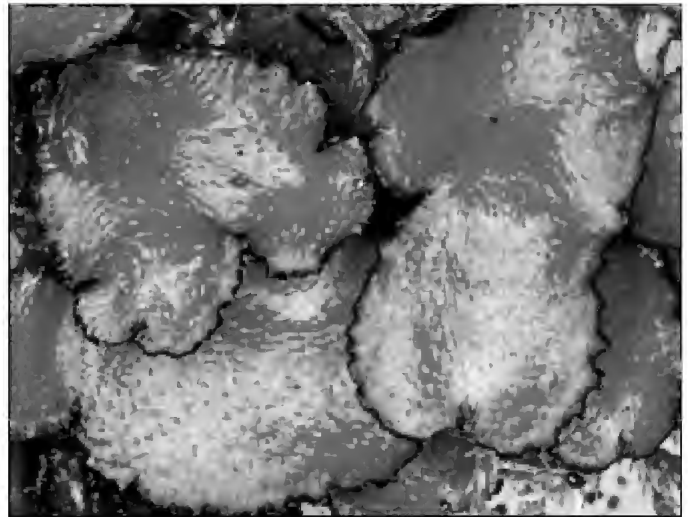


Fig. 1. *Reboulia hemispherica*, one of the most common complex thalloid liverworts in the GNF. The air pores can be seen as white dots on the dorsal surface of the thalli. Also note the dark purple scales that extend from the ventral surface to the edges of the thalli.



Fig. 2. *Porella platyphylla* (5× macro). This leafy liverwort is common on rocks near streams in New Mexico and the GNF. The leaves have a complicate bilobed architecture. Viewed under a compound microscope, the cells of the leaves would have small oil bodies.

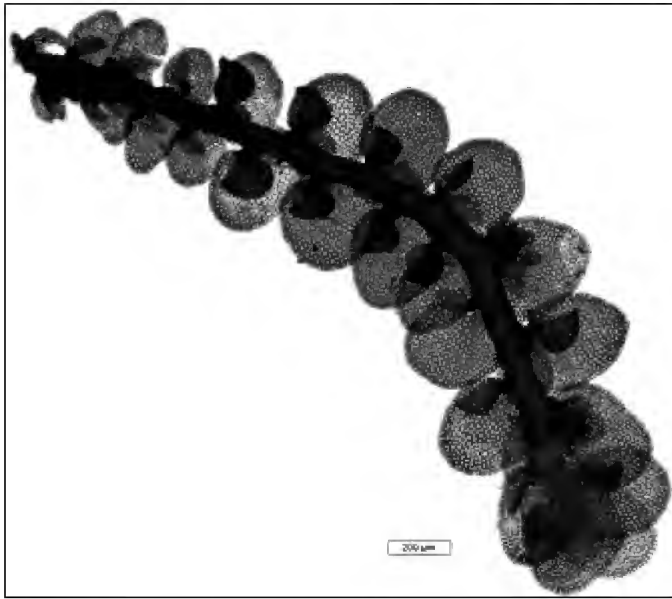


Fig. 3. Photomicrograph (40×) of *Frullania riparia*. This leafy liverwort is common in the GNF. Note that each leaf has two lobes, with the smaller lobe folded under the larger lobe, making it a complicate bilobed plant. Mosses never have this kind of morphology.

in mosses. Most leafy liverworts have microscopic oil bodies within the cells of their leaves, which can be important in species identification; mosses never contain oil bodies. These oil bodies can be transient and are best examined in fresh specimens, although they seem to persist for months in dried specimens collected from arid environments.

In this manuscript, we present a listing of the liverworts that have been reported to occur in New Mexico, including a number of species new to the state that have not been reported elsewhere (personal communications in 2013 from R. D. Worthington and K. B. Romig). In addition, we have undertaken a study to document which liverworts occur in the Gila National Forest (GNF), and we report the initial findings of this ongoing study.

Study Area

The GNF consists of 1.3 million ha (3.3 million ac) of varied terrain with elevations varying from 1,295 m (4,250 ft) to 3,321 m (10,895 ft). The geography is defined by the Gila River and its tributaries, and the associated mountain ranges and canyons. Major mountain ranges include the Mogollon, Black, Silver City, Pinos Altos, Tularosa, and Burro ranges. The Gila Cliff Dwellings National Monument is included in the study area.

The habitats of the GNF are remarkably varied. At lower elevations in more arid regions, Chihuahuan desert scrubland is found. At more moderate elevations (1,676–2,133 m, 5,500–7,000 ft), pinyon-juniper-oak forests and mixed-conifer forests predominate. Ponderosa pine forest is found at higher elevations (2,133–2,743 m, 7,000–9,000 ft). Spruce-fir

forests occur above 2,743 m (9,000 ft). Riparian habitats are defined as being immediately along water courses. Additional information is provided in Kleinman and colleagues (2014).

Methods

The written literature on New Mexico hepatics is not extensive (Standley 1915, 1916; Evans 1922; Arsene 1933; Little 1937; Frye and Clark 1937–47; Little 1942; Shields 1954; Bird 1960; Prior 1969; Guerke 1971; Ireland et al. 1981; Stark and Castetter 1982; Whittemore 1995; Worthington 2001; Romig 2012). We reviewed this literature and searched bryophyte databases (Consortium of North American Bryophyte Herbaria, Southwest Environmental Information Network). We standardized the nomenclature but did not confirm the identity of reported specimens.

We obtained a research and collection permit from the GNF supervisor and in 2010 began collecting specimens of liverworts; to date, approximately 80 specimens have been collected. We have collected from representative areas in all major habitats, except for spruce-fir forests, where access is difficult. Individual collections consisted of approximately 4 cm² of material; documentation was made of the date, location, habitat, substrate, and associated vascular plant species. Voucher specimens have been placed in the Dale A. Zimmerman Herbarium (SNM) at Western New Mexico University. Photographs of all species are available on the website <http://www.gilaflorea.com>.

Specimens were identified with the aid of published references (Hong 1989, 1992; Hicks 1992; Doyle and Stotler 2006; Damsholt 2009) and with the assistance of experts mentioned in the acknowledgments. The nomenclature reference source for this list is the Tropicos website (<http://www.tropicos.org>), maintained by the Missouri Botanical Garden.

Results

Liverworts are uncommon, but not rare, in New Mexico. We have compiled a list of 73 taxa of liverworts in 23 families, including the specimens we collected (Table 1). This table includes a number of species new to the state, collected by Dr. Richard Worthington and by Kirsten Romig (pers. comm., 2013). Of these taxa, 22 species in 7 families are complex thalloid liverworts. Simple thalloid liverworts are represented by 5 taxa in 4 families. Leafy liverworts are more diverse in New Mexico; 46 taxa in 12 families have been reported in the state.

Reported field occurrence of liverworts varies widely by species, as would be expected. In the literature, the most commonly reported thalloid liverwort species are *Marchantia polymorpha* (more than 30 collections), *Reboulia hemispherica* (almost 20 collections; Fig. 1), and *Plagiochasma wrightii* (almost 20 collections). Leafy liverworts are both more common and more diverse in New Mexico, with the most commonly reported taxa being *Porella platyphylla* (with almost 40 collections; Fig. 2) and *Frullania inflata* (25 collections; Fig. 3). In

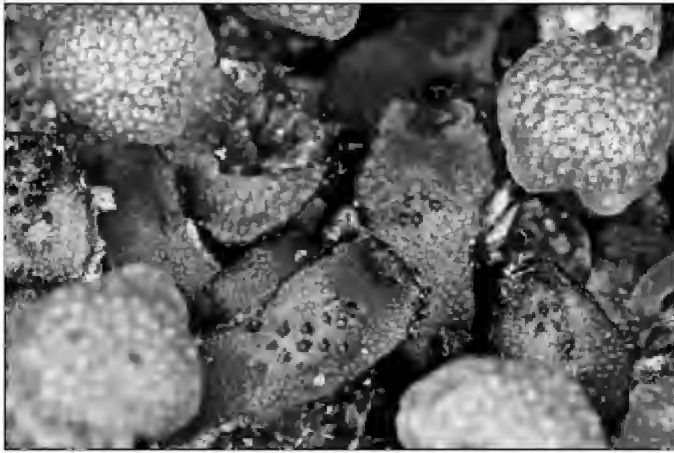


Fig. 4. *Mannia californica*, thalli and reproductive structures (3× macro). The small black nodules on the surface of the thalli house antheridia, male reproductive structures. The large green spheroids are the carpocephala, where the spores will be produced.

contrast, there are several species for which only a single collection has been reported; ideally these would be reconfirmed.

The GNF has been relatively under-represented in bryophyte studies in the state. Before we began our study, only 13 taxa had been described from the GNF (Table 2), the majority of those collected by Worthington. So far, we have confirmed the occurrence of 9 of these taxa and have added 9 more taxa to the list, for a total of 22 taxa. We have discovered 2 taxa new to New Mexico. *Mannia californica* (Fig. 4) was found in three locations, growing on rock or sandy soil, in mixed-conifer, pinyon-juniper-oak, and ponderosa pine forest. A species of *Fossombronia* (Fig. 5) was found growing among *Encalypta ciliata* Hedwig in ponderosa pine forest. This represents a liverwort family new to New Mexico. This plant

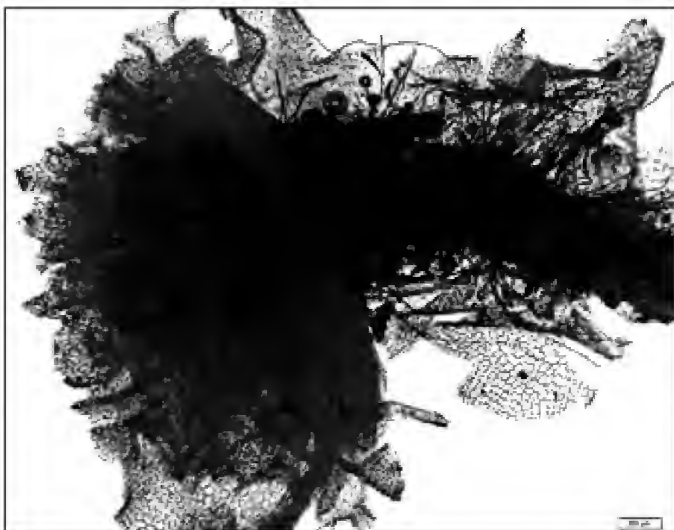


Fig. 5. *Fossombronia*, 40× photomicrograph, a liverwort new to New Mexico. The purple rhizoids are characteristic.

has yet to be identified to species, because spore morphology is required for definitive identification and the plant has not been found in a reproductive state.

The most commonly collected thalloid liverwort was *Reboulia hemispherica* (Table 2). The most commonly collected leafy liverworts were *Porella platyphylla* and *Frullania* species. These data are in accordance with what has been reported in the literature for New Mexico.

Most leafy liverworts were found in mixed-conifer forests. *Chiloscyphus polyanthos*, *Jungermannia exsertifolia*, and *Plagiochila asplenoides* were found in riparian habitats. The complex thalloid liverworts were more cosmopolitan, and were found in pinyon-juniper-oak, mixed-conifer, ponderosa pine, and riparian habitats. *Mannia fragrans* was found in a ponderosa pine forest that had burned. To date, no liverworts have been found in arid desert environments in the GNF, although we have found *Plagiochasma rupestre* in desert habitat outside the GNF.

Discussion

Approximately 73 liverwort taxa are known to occur in New Mexico, compared with 46 species reported from Nevada (Brinda et al. 2007), 60 from Utah (Flowers 1961), and 142 from California (Doyle and Stotler 2006). A relatively small percentage (30%) of the liverwort species that have been reported to occur in New Mexico have been found in the Gila National Forest. There may be several explanations for this. A major reason is that liverworts are unfamiliar to most botanists and therefore are rarely collected or identified. Also, although thalloid liverworts are relatively arid-adapted, leafy liverworts appear to be less so. They are more likely to occur in moist areas at higher elevations that are more difficult to reach. Unfortunately, one of the best sites for liverworts in our study, Bead Spring in the Mogollon Mountains, succumbed to the Whitewater-Baldy Complex forest fire in 2012. Those populations may take years to recover, if they recover at all. Additionally, we might speculate that climate change and the changing distribution of rainfall may make liverworts more scarce. Nevertheless, continuing investigation and collection of liverwort species should be undertaken to document the prevalence of these lovely little plants in our area.

Acknowledgments

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Table 1. Checklist of New Mexico Liverworts

Complex Thalloid

Aytoniaceae

- Asterella gracilis* (F.Weber) Underw. [Ireland et al. 1981]
Asterella palmeri (Austin) Underw. [Arsène 1933]
Mannia californica (Gottsche) L.C. Wheeler [Blisard & Kleinman 2012-2-23-1, SNM]
Mannia fragrans (Balb.) Frye & L. Clark [Standley 1916; Arsène 1933]
Mannia paradoxa R.M. Schust. [Schuster 1992, p 401–8]
Mannia pilosa (Hornem.) Frye & L. Clark [Worthington 6927, NYBG]
Plagiochasma rupestre (G. Forst.) Stephani [Standley 1915; Arsène 1933; Little 1937; Stark and Castetter 1982]
Plagiochasma wrightii Sull. [Arsène 1933; Stark and Castetter 1982]
Reboulia hemisphaerica (L.) Raddi [Standley 1915; Arsène 1933]

Cleveaceae

- Athalamia hyalina* (Sommerf.) S. Hatt. [Shields 1954]

Conocephalaceae

- Conocephalum salebrosum* Szweyk., Buczkowska & Odrzykoski¹ [Standley 1915; Arsène 1933]

Marchantiaceae

- Dumotiera hirsuta* (Sw.) Nees [Shields 1954]
Marchantia polymorpha L. [Standley 1915; Arsène 1933; Stark and Castetter 1982]

Oxymitraceae

- Oxymitra androgyna* M. Howe [Prior 1969]

Ricciaceae

- Riccia albolimbata* S.W. Arnell [Worthington 34182, NYBG]
Riccia austinii Stephani [Little 1942]
Riccia campbelliana M. Howe [Worthington 32691, NYBG]
Riccia cavernosa Hoffm. [Little 1942]
Riccia frostii Austin [Arsène 1933; Little 1937]
Riccia membranacea Gottsche & Lindenb. [Arsène 1933]
Riccia sorocarpa Bisch. [Little 1942]

Targioniaceae

- Targionia hypophylla* L. [Shields 1954]

Simple Thalloid

Blasiaceae

- Blasia pusilla* L. [Evans 1922]

Fossombroniaceae

- Fossombronia* sp. Raddi [Blisard & Kleinman 2011-10-13-6, SNM]

Metzgeriaceae

- Apometzgeria pubescens* (Shrank) Kuwah. [Shields 1954]
Metzgeria conjugata Lindb. [Arsène 1933]

Pelliaceae

- Pellia endiviifolia* (Dicks.) Dumort. [Worthington 32598, NYBG]

Leafy

Anastrophyllaceae

- Barbilophozia barbata* (Schreb.) Loeske [Arsène 1933]
Barbilophozia floerkei (F. Weber & D. Mohr) Loeske [Frye and Clark 1937–47]
Barbilophozia hatcheri (A. Evans) Loeske [Shields 1954]
Barbilophozia lycopodioides (Wallr.) Loeske [Standley 1916; Arsène 1933]
Gymnocolea inflata (Huds.) Dumort. [Romig 185, NMC]

Blepharostomaceae

- Blepharostoma trichophyllum* (L.) Dumort. [Arsène 1933]

Cephaloziaceae

- Cephalozia lunulifolia* (Dumort.) Dumort. [Shields 1954]
Cephalozia pleniceps (Aust.) Lindb. [Arsène 1933]
Odontoschisma denudatum (Nees) Dumort. [Prior 1969]
Odontoschisma prostratum (Sw.) Trevis [Prior 1969]

Cephaloziellaceae

- Cephaloziella divaricata* (Sm.) Schiffn. [Shields 1954; Stark and Castetter 1982]
Cephaloziella hampeana (Nees) Schiffn. ex Loeske [Shields 1954]
Cephaloziella rubella (Nees) Warnst. [McGregor 7477, NYBG]

Jubulaceae

- Frullania brittoniae* A. Evans [Worthington 22248, UTEP]
Frullania eboracensis Gottsche [Standley 1915; Arsène 1933; Shields 1954]
Frullania inflata Gottsche [Standley 1916; Arsène 1933; Stark and Castetter 1982]
Frullania pluricarinata Gottsche² [Hentschel et al. 2009]
Frullania riparia Hampe ex Lehm. [Standley 1916]

Jungermanniaceae

- Jamesoniella autumnalis* (DC.) Stephani [Prior 1969]
Jungermannia confertissima Nees [Prior 1969]
Jungermannia exsertifolia Stephani [Prior 1969]
Jungermannia hyalina Lyell [Arsène 1933]
Jungermannia leiantha Grolle [Worthington 30657, NYBG]
Jungermannia pumila With. [Prior 1969]
Jungermannia sphaerocarpa Hook [Worthington 32667, UNM]
Lophozia collaris (Mart.) Dumort. [Worthington 32621, NYBG]
Lophozia confertifolia Schiffn.³ [Arsène 1933]
Lophozia incisa (Schrad.) Dumort. [Arsène 1933]
Lophozia ventricosa (Dicks.) Dumort.³ [Romig 97, NMC; Blisard & Kleinman 2012-5-14-1, SNM]
Lophozia wenzelii (Nees) Stephani³ [Buck 39716, NYBG; Worthington 30657, UNM]

Lepidoziaceae

- Lepidozia reptans* (L.) Dumort. [Arsène 1933]

Lophocoleaceae

- Chiloscyphus minor* Nees [Arsène 1933]
Chiloscyphus pallescens (Ehrh. ex Hoffm.) Dumort. [Worthington 25476, NYBG]
Chiloscyphus polyanthos (L.) Corda [Arsène 19037, NYBG]
Chiloscyphus rivularis (Schrad.) Hazsl. [Standley 1915; Arsène 1933]

Plagiochilaceae

- Plagiochila asplenoides* subsp. *porelloides* (Torr. ex Nees) R.M. Schust.⁴ [Arsène 1933]

Porrelaceae

- Porella cordaeana* (Huebener) Moore [Worthington 32690, NYBG]
Porella pinnata L. [Prior 1969]
Porella platyphylla (L.) Pfeiff.⁵ [Standley 1915; Arsène 1933; Stark and Castetter 1982]

Radulaceae

- Radula bolanderi* Gottsche [Guerke 1971]
Radula complanata (L.) Dumort. [Arsène 1933; Stark and Castetter 1982]

Scapaniaceae

- Scapania apiculata* Spruce [Arsène 1933]
Scapania curta (Mart.) Dumort. [Arsène 19080, NYBG]
Scapania cuspiduligera (Nees) Muell. Frib. [Shields 1954]
Scapania subalpina (Nees ex Lindenb.) Dumort. [Arsène 20304, NYBG]
Scapania undulata (L.) Dumort. [Arsène 1933]

Notes

1. *Conocephalum conicum* L. and *Conocephalum salebrosum* Szweyk., Buczkowska & Odrzykoski have been recently separated by morphologic criteria and molecular methods. According to these authors, *C. salebrosum* is the species that occurs in North America (Szweykowski et al. 2005).
2. This species was identified by molecular methods (Hentschel et al. 2009), although it can be identified by morphologic criteria.
3. All three of these species, *L. confertifolia*, *L. ventricosa*, and *L. wenzelii*, are listed as separate species on the Tropicos.org website. However, not all authors agree.
4. According to Hong (1922), this is the only subspecies that occurs in NM.
5. *Porella platyphylla* (L.) Pfeiff. and *Porella platyphylloidea* (Schwein.) Lindb. appear to be examples of so-called cryptic species, which cannot be differentiated solely on the basis of morphologic characteristics but require molecular studies for species identification (Therrien et al. 1998; Heinrichs et al. 2011). Both these species are being included under *P. platyphylla*.

Table 2. Liverworts of the Gila National Forest

Family	Complex Thalloid Liverworts	# Specimens Collected ⁴
Aytoniaceae	<i>Mannia californica</i> (Gottsche) L.C. Wheeler ³	6
	<i>Mannia fragrans</i> (Balb.) Frye & L. Clark ³	5
	<i>Plagiochasma wrightii</i> Sull. ³	1
	<i>Reboulia hemisphaerica</i> (L.) Raddi ²	11
Marchantiaceae	<i>Marchantia polymorpha</i> L. ²	4
Ricciaceae	<i>Riccia campbelliana</i> M. Howe ¹	
Simple Thalloid Liverworts		
Fossombroniaceae	<i>Fossombronia</i> sp. Raddi ³	2
Leafy Liverworts		
Anastrophyllaceae	<i>Barbilophozia barbata</i> (Schreb.) Loeske	2
	<i>Barbilophozia floerkei</i> (F. Weber & D. Mohr) Loeske	
Cephaloziellaceae	<i>Cephaloziella divaricata</i> (Sm.) Schiffn. ²	3
Jubulaceae	<i>Frullania inflata</i> Gottsche ²	9
	<i>Frullania riparia</i> Hampe ex Lehm. ²	3
Jungermanniaceae	<i>Jungermannia exsertifolia</i> Stephani ³	1
	<i>Jungermannia leiantha</i> Grolle ³	1
	<i>Jungermannia sphaerocarpa</i> Hook ¹	
	<i>Lophozia ventricosa</i> (Dicks.) Dumort. ³	1
Lepidoziaceae	<i>Lepidozia reptans</i> (L.) Dumort. ²	1
Lophocoleaceae	<i>Chiloscyphus polyanthos</i> (L.) Corda ³	3
Plagiochilaceae	<i>Plagiochila asplenioides</i> subsp. <i>porelloides</i> (Torr. ex Nees) R.M. Schust. ²	3
Porellaceae	<i>Porella cordaeana</i> (Huebener) Moore ¹	
	<i>Porella platyphylla</i> (L.) Pfeiff. ²	14
Radulaceae	<i>Radula complanata</i> (L.) Dumort. ²	4

Notes

1. Known from the GNF prior to our study
2. Known from the GNF prior to our study and confirmed by us
3. Found by us, new to the GNF
4. Number of specimens collected in our study

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An Overview of Aridland Ciénagas, with Proposals for Their Classification, Restoration, and Preservation

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Abstract

Ciénagas are the American Southwest's most unusual wetlands, yet they are dwindling. This paper addresses what they are, their uniqueness and importance, how they developed, and the causes for the loss of most ciénaga habitat. We also propose a classification system for ciénagas that will contribute to a more meaningful and better-focused discussion about ciénagas, provide an inventory of known ciénagas, and suggest a system of Ciénaga Coordinators with the goal of identifying, restoring, and preserving the few remaining ciénagas. Finally, the inventory from this paper is made available online in an interactive, open, moderated format that will allow anyone to contribute to the correction, evolution, and general improvement and growth of this database, and to download and use the content. A link to this system can be found in a permanent archive of this paper at <http://hdl.handle.net/2152/30285>.

Introduction

The general public knows what rivers are, and even people unconcerned about the environment understand the importance of drinking water and watercourses such as rivers, creeks, streams, and brooks. But there is a unique wetland in the American Southwest that not many people know at all: the aridland ciénaga. Few uncompromised ciénagas remain functional, and, absent an awareness of what and how important they are, we may soon see these endangered wetlands become extinct. The Endangered Species Act does not yet protect habitats independently of individual species, but if it did, ciénagas would undoubtedly receive protection. *Ciénaga* is a Spanish term used in the Southwest for a silty marshy area, a bog, or a shallow, slow-moving flow of water through dense surface vegetation (Hendrickson and Minckley 1985; Minckley et al. 2009). We provide a discussion of the source and alternate spellings and punctuation of this term in Appendix A.

Our interest in ciénagas emerged from an undertaking to restore the 14.48-km (9-mi), severely incised—deeply down-cut or eroded by rapid water flows—reach of the Burro Cienaga on the Pitchfork Ranch in Grant County, New Mexico, in the southwest corner of the state (Cole and Cole 2010; Helbock and Cole 2014). In this paper, we answer the following questions about this imperiled ecosystem: What is a ciénaga? How and when did ciénagas form, what damaged them, what were their historic numbers, how much or what percentage of ciénaga habitat remains, and why are ciénagas

important to the Southwest? Will a ciénaga classification system and the creation of Ciénaga Coordinators help to restore and preserve them?

Ciénagas Defined

Undamaged ciénagas are freshwater or alkaline wet meadows with shallow-gradient, permanently saturated soils in otherwise arid landscapes that in earlier time supported lush meadow grasses and often occupied the entire widths of valley bottoms. Ciénagas occur because the geomorphology forces water to the surface, and historically they covered large areas rather than occurring as single pools or channels (Hendrickson and Minckley 1985; Sivinski and Tonne 2011). Ciénagas are usually associated with seeps or springs and are occasionally found in canyon headwaters or along the margins of streams (Sivinski and Tonne 2011). In a healthy ciénaga, water slowly migrates through long, wide mats of thick, sponge-like wetland sod. Ciénaga soils are squishy, permanently saturated, organic, anaerobic, and black.

Highly adapted grasses (Poaceae), sedges (Cyperaceae), and rushes (Juncaceae) are the dominant plants in ciénagas, with riparian tree species—Goodding's willow (*Salix gooddingii*), Fremont's cottonwood (*Populus fremontii*), and scattered Arizona walnuts (*Juglans major*)—found along drier margins or down-valley where the ciénaga ends and water disappears underground. The telltale signs of an aridland ciénaga are ground-fed persistent water, gray or oxidized soils, soil fines (silts, clay, and organic particles) or near fines, and often the occurrence of plants endemic to ciénagas.

Since the late 1800s, many of these ciénagas have lost their instream or wetland function; unincised ciénagas are essentially nonexistent today (Minckley et al. 2009) and most ciénagas are substantially reduced in size, with successful tree species common along deeply cut channels due to the ongoing, region-wide erosion that followed the arrival of Europeans (Fig. 1). As described below, the misuse of land by frontiersmen entrenched water flow between what became vertical walls and established incisions that have resulted in an ever-worsening erosive process and drawdown of local water tables (Fig. 2). Some southwestern ciénagas have simply dried up because their aquifers were captured and depleted for farming or industrial purposes (Sivinski and Tonne 2011). This pervasive drying of most marshland environments left behind few ciénagas and those that survived are significantly reduced in size. Many of the remaining ciénagas look and function like creeks: narrow, incised, and continuing to de-



Fig. 1. Looking down-channel, creek-like portion of the Burro Cienaga, Pitchfork Ranch, Grant County, in southwest New Mexico. Photo: Dennis O'Keefe (2008).

grade (Fig. 3). Since the late 1800s, natural wetlands in arid and semi-arid desert grasslands of the American Southwest and Northern Mexico have largely disappeared (Minckley and Brunelle 2007).

Hendrickson and Minckley (1985) first alerted the Southwest academic world to the importance of the region's overlooked *ciénagas*. Prior to that time, many believed that the only good wetland was a drained wetland (McCool 2012). However, since Hendrickson and Minckley's (1985) rather inauspicious invitation for further study of *ciénagas*, the efforts to understand and restore them have gained prominence.

A sense of how poorly *ciénagas* had been viewed historically can be gleaned from a remark made during the naming of Silver City, New Mexico. When city fathers met in 1870 to choose a name for the community occupying the once unmolested *La Ciénega de San Vicente*, a lengthy discussion finally reached consensus to discard *San Vicente* and to call their new town *Silver City*. Upon hearing the choice, one of the men in attendance remarked: "It was one hell of a name to call a town on a mud flat" (Alexander 2005, 89).

Similarly, consider this excerpt from the beloved New Mexico novel *Red Sky at Morning* (Bradford 1968). In this 1940s-era conversation between the narrator, Joshua Arnold, and his classmate, this exchange occurs (p. 86):

"I didn't know there was this much water around Sagrado . . . [t]he Sagrado River's been dry since I got here."

"This is a *ciénega*," Parker said. "It's some kind of underground spring, but it's not good for anything but making the ground wet. Costs a fortune to drain it or pump it off, and Cloyd isn't about to spend money for things like that."

The *ciénagas* discussed here are not to be confused with typical wetlands found throughout the North American continent. What distinguishes "aridland *ciénagas*" is their location in deserts and their association with groundwater discharge—springs and groundwater seeps in otherwise arid lands—which lends them a large degree of permanence, biogeographic isolation, and stability.

Ciénagas are commonly overlooked but are an important subset of wetlands in the North American Southwest. A recent study (Dahl 2011) looked at the extent and habitat type of wetlands throughout the conterminous United States and concluded that there were an estimated 44.6 million ha (110.1 million ac) of wetland habitat. Despite this comprehensive survey and detailed treatment of a wide variety of wetlands—freshwater and saltwater, marshes and ponds, and even descriptive types such as prairie pothole wetlands—the report makes no mention of *ciénagas*.

Southwest aridland *ciénagas* discussed here differ from the *ciénaga* wetlands of Colombia and other South American countries. There are many dozens of wetlands bearing the name "*ciénaga*," covering more than 7,800 km (4,847 mi) in Colombia alone (Subgerencia Cultural del Banco de la República 2005), but those are not the desert groundwater-fed *ciénagas* of the Southwest. The Colombian *ciénagas* represent different wetland systems altogether. Perhaps those studying *ciénagas* would do well to refer to the *ciénagas* mentioned in the Southwest as "aridland *ciénagas*," thereby avoiding confusion with high-mountain wet meadows and other wetland *ciénagas* elsewhere that function differently.



Fig. 2. The eight-foot wall shown here, down-channel right, is typical of the incision damage in many *ciénagas*. This pool, not a typical feature in a healthy *ciénaga*, is located in kilometer 1 of the 14 km (9 mi) Burro Cienaga reach on the Pitchfork Ranch. Photo: Cinda Cole (2005).



Fig. 3. Looking up-channel, a short section of the approximately 3.2 km (2 mi) ciénaga portion of the 14.48 km (9 mi) reach of the Burro Ciénaga (full course is 747.2 km, 47.6 mi) on the Pitchfork Ranch, is the result of redirecting the broad ciénaga flow into what became a creek-like incision. This resulted from an effort to avoid flooding two later abandoned agriculture fields, situated down-channel left or on viewer's right. Before this ciénaga was damaged, it likely migrated through the entire valley width shown here. Photo: Cinda Cole (2007).

The Importance of Ciénagas

The importance of ciénagas cannot be overstated. Their frequent association with springs endows them with a considerable degree of permanence and endemism, thereby providing critical habitat for an abundance of distinctive and rare plant and animal species (Hendrickson and Minckley 1985; Sivinski and Tonne 2011). Wetlands in the Southwest occupy less than 2% of the land area but have an enormous impact on the region (Webb et al. 2007). Before the arrival of Europeans, these boggy wetlands often extended from one canyon wall to the other, wetting valley bottoms that were broader than a football field is long.

Wetlands are critical habitat for many at-risk species. Approximately 80% of all of New Mexico's sensitive vertebrate species that are listed as threatened or endangered depend on riparian or aquatic habitat at some time during their life cycle (New Mexico Department of Game and Fish 2000). Of the 1,320 species in the United States listed as either threatened or endangered under the Endangered Species Act, 573 are animal species and nearly half of these live in aquatic environments (McCool 2012).

Beyond its value to endemic, threatened, and endangered species, ciénaga restoration will better support all wildlife; improving habitat in otherwise arid regions will result in desert ciénagas and riparian corridors that are increased in size and consequently hold more water. Though ciénagas have long been overlooked in conservation priority assessments, scientists have argued for increasing the priority of ciénaga conservation because of the typically high endemism and habitat diversity of desert wetlands (Minckley et al. 2013). Ciénaga restoration—installing a wide variety and large number of grade-control structures—slows floods and flows, increases seepage and wicking, broadens wetlands, raises water tables, and thereby enlarges ciénagas and riparian corridors (Minckley et al. 2013).

Over the course of the last decade, the ciénaga restoration project on the Pitchfork Ranch—still less than half complete—has included the installation of more than 200 grade-control structures that have raised the water table nearly 0.3 m (1 ft), have raised the entire watercourse bed more than 0.3 m (1 ft) throughout the ranch's 14.5-km (9-mi) reach of the Burro Ciénaga, have correspondingly raised the level of the surface water, have widened and “shallowed” the channel, have captured 27 Mg (30 ton) of sediment, have increased vegetation, and have caused surface water to extend farther down-channel for a longer period of time before water recedes underground. The results of restoration can be seen from the pair of same-location photographs in Figure 4.

Archaeological sites frequently surround ciénagas and contain evidence of Native American land use and fossil remains of prehistoric animals (Hendrickson and Minckley 1985). Researchers are currently analyzing charcoal, pollen, and stable isotopes preserved in ciénaga sediment in order to uncover the development and history of the region (Meyer 1973; Minckley and Brunelle 2007; Minckley et al. 2009; Brunelle et al. 2010). By matching these data with tree-ring and fire data, researchers are bringing the region's history into increasing clarity (Davis et al. 2002).

The implication of disappearing ciénagas in the arid Southwest is even more worrisome when viewed in the context of the availability of the world's potable water. Only 3% of the globe's water supply is freshwater, and of that, 69% is locked up in ice and glaciers and 30% occurs underground, leaving less than 1% of the Earth's freshwater available as surface water (Gleick 1993). Importantly, although typically given little thought, ciénagas are freshwater. The degradation and loss of wetlands is more rapid than that of other ecosystems (Millennium Ecosystem Assessment 2005). In a global context, destruction of the few remaining ciénaga wetlands may seem minuscule, but when ciénagas are viewed as a source of aridland surface water, the losses have enormous



Fig. 4. These photographs were taken from the same location on July 18, 2005, and September 26, 2014. Notice Soldier's Farewell Hill in the background at about 12 km (8 mi) of the Burro Cienaga and the cholla cactus skeleton, lower left. The top photograph was taken after the boulder baffle was installed and coyote willows were planted, down-channel right, mid-picture. Photos: Cinda Cole (2005 and 2014).

importance, especially to the endemic plants and animals that coevolved with and are dependent on these systems.

Ciénagas also provide *ecosystem services* (White 2008; Millennium Ecosystem Assessment 2005). This is an emerging restoration notion in which market value is attributed to a variety of environmental functions provided by landowners for the public good and for which they have historically not been compensated. These services include filtering rain and snow-melt, slowing seasonal flood pulses to reduce stream-channel degradation and slow soil erosion, promoting groundwater recharge, and delivering clean, safe drinking water at a far lower cost than would be required to build infrastructure to

replace these habitats and their services. Although underrecognized, when both the marketed and nonmarketed economic benefits of wetlands are included, the total economic value of unconverted wetlands is often greater than that of converted or dewatered wetlands (Millennium Ecosystem Assessment 2005).

A recently touted ecosystem service that further strengthens the importance of ciénagas is the notion of the “carbon sequestering sweet spot” (White 2014). Thousands of years of careless land use has caused the release of nearly 80% of carbon—up to 80 billion tons—from the world's soil into the atmosphere (White 2014). Increasingly, soil researchers note that responsible soil management can recapture most of the misplaced carbon by bringing soil back to health, creating opportunities for plants to capture and convert sunlight into high-energy sugars and break down atmospheric carbon dioxide into oxygen (Ohlson 2014). Wetlands are the world's best ecosystems for capturing and storing carbon in their soils (White 2014). There are few “carbon sinks” in the arid Southwest and we posit that none are superior to rich, dark ciénaga soils.

Ciénagas also have cultural implications. Water serves multiple vital purposes, one of which is often overlooked but lends weight to the merit of restoring ciénagas. Ciénagas play a sacred and functional role in the lives of many Native Americans, as Indigenous People traditionally consider springs to be alive. They were points where creation came to the surface and spilled out, where a hand could reach down and feel life surfacing (Childs 2000).

Aggradation and Degradation of Aridland Ciénagas

We suggest two perspectives for studying the history of aridland ciénagas: (1) their development during the 10,000 years before Anglo-European entry to the Southwest, and (2) the incision and dewatering processes that impacted them after Anglo-European settlement. Both are important, but ciénaga damage and disappearance will be prioritized and discussed

first, as these losses are ongoing and require immediate attention. Although scientists studying ciénagas have only recently begun the daunting task of teasing out the natural processes that established them, the explanation for ciénaga deterioration and loss is clear. In less than 200 years, a series of mostly human-caused events joined forces to transform these lands from a depositional environment to an erosional one, severely lowering groundwater tables and resulting in the loss of most ciénaga habitat. What nature painstakingly assembled over a period of some 10,000 years, we brought asunder in less than 200 years (Minckley et al. 2012).

Seven Factors Responsible for Ciénaga Degradation and Disappearance

The causes for ciénaga dewatering in the Southwest are complex. The seven factors below are causal factors driving ciénaga dewatering and the general desertification of the Southwest.

1. Sheep Introduction. The disappearance of ciénagas began with the introduction of livestock by the Spanish. The first documented arrival of livestock in the Southwest was in 1598 with Juan de Oñate and his party of colonists, who introduced sheep. By the late 1700s, sheep were a major regional industry (Dunmire 2013). One of the descriptions on Miera's 1758 map—the earliest of New Mexico—put sheep numbers held by Spanish and Puebloan herders at 115,826 animals (Kessell 1979). By 1865, the count of sheep had more than doubled and the ratio of sheep to cattle ballooned to 37 to 1—4,600,000 sheep to 125,000 cattle (Dunmire 2013). The land could not withstand the grazing pressure of these animals; barren soil, erosion, and arroyo cutting resulted from severe overgrazing (Hendrickson and Minckley 1985).

2. Beaver Eradication. Ciénaga dewatering worsened with the overtrapping of beaver (*Castor canadensis*) in the 1820s–1830s (McNamee 1994). Beaver are capable of building as many as 20 dams per 1.6 km (1 mi) of stream, causing water to course across the landscape, transforming otherwise rushing flows into a series of pools and murky wetlands linked by shallow, multiple-branched channels (Mann 2011). Untold numbers of beaver lodges once dotted desert waterways, forming reservoirs that helped control seasonal flooding, which in turn thwarted erosive processes.

When beaver were trapped out of southwestern rivers, shallow flatland watercourses and adjacent riparian zones created by beaver shifted from complex systems dominated by ponds, multiple channels, ciénagas, marshes, and otherwise wide wetlands plentiful in fish and wildlife into simple, incised, single-thread channels with narrow strips of riparian vegetation (Wild 2011). In a short period of time, beaver were virtually trapped out of southwestern rivers, a second step in converting dynamic and complex stream and river ecosystems into the relatively static and simplified water delivery systems of today (Wild 2011).

3. Agricultural Recontouring and Aquifer Depletion. Many ciénagas also suffered damage when early settlers recontoured the broad ciénaga canyon flats in a misguided attempt to prevent the flooding of their agricultural fields. The Pitchfork Ranch has two of these recontoured and now abandoned fields (Fig. 3). Throughout the Southwest, remnant ditches, dikes, and dams persist today throughout many of the old canyon fields near the few remaining and poorly functioning ciénagas (Minckley et al. 2012). The resulting channelization and concentrated flow have reduced these historic wetlands to a fraction of their original size and inadvertently created deep, high-walled incisions that have progressively worsened—though most farming has long since ceased—and lowered the groundwater table even more, further dewatering formally wetted ciénaga habitat (Fig. 2).

As we have pointed out, not all ciénagas follow the same pattern of degradation and disappearance. For example, with little upland or channel erosion, irrigation-well pumping for cotton farms is almost entirely responsible for the final demise of the huge San Simon Cienega in Hidalgo County, New Mexico. The small ciénagas surrounding Apache Tejo Kennecott Warm and Kennecott Cold Springs near Hurley, New Mexico, were dried up primarily by water wells drilled into them for the copper smelter. The aquifer for the huge Comanche Springs Cienega in west Texas was captured and depleted by the urban wells of the City of Fort Stockton (Sivinski and Tonne 2011; Sivinski, pers. comm. April 2015).

4. The Rise of Cattle Ranching. The damage caused by sheep, the decimation of beaver, conversion of land to agricultural fields, and aquifer depletion was worsened in the 1880s with the overstocking of cattle (Bahre 1991). Channel incision occurred throughout the Southwest due to livestock trails, as well as old wagon roads and “two-track” trails (Zeedyk 2006). Grass cover dominated the landscape through mid-century but, due to ranching, began to disappear by the 1880s, accompanied by the explosion of mesquite and creosote as woody plants outcompeted the once ubiquitous, now overgrazed grasses (Bahre 1991; Dunmire 2013). In 1865 the ratio of sheep to cattle was 37:1, yet within 25 years the ratio had narrowed to less than 2:1—3,492,800 sheep to 1,809,400 cattle (Dunmire 2013). In little more than a century, sheep ranching went from New Mexico's leading industry to one of minor importance (Dunmire 2013). Near the onset of severe overgrazing—including congestion in wetlands—the well-documented cycle of arroyo cutting accelerated the destruction of ciénagas (Hendrickson and Minckley 1985).

5. Drought. Drought—the only natural or non-legacy cause of ciénaga dewatering—has always been central to the Southwest, but severe weather and drought exacerbated the problems of the beaverless, recontoured, and overstocked landscape and the severely degraded grasslands and wetlands (Hendrickson and Minckley 1985).

6. Fire Suppression. The elimination of fire from the Southwest also caused significant habitat changes to ciénagas. Prior to European arrival, burning was frequent enough to exclude most woody plants, while promoting the growth of grass species (Davis et al. 2002). This frequent fire regime was a well-established, natural intervention that allowed grasses to outcompete woody plants. The near absence of fire following European arrival transformed pre-European grasslands to woodlands, facilitating erosion and contributing to ciénaga losses (Davis et al. 2002).

7. Human-Caused Climate Change. Although climate change has not been noted as a significant source of damage to ciénagas, it will in the future, as there is now irrefutable scientific consensus that the human global systems of commerce and energy are degrading the natural global systems that support life on the planet, posing an enormous long-term threat to life as we know it (Klein 2014). Climate change may well turn out to be the worst of these seven ills, as human activities have already changed the climate of the Southwest.

Scholars are offering increasingly dire projections (Saunders et al. 2008). Megadroughts are predicted for the Central Plains and the Southwest by the end of the 21st century, and the Southwest could experience the driest conditions in a millennium (Yeager 2015).

Climate change is already affecting the American West more than any other part of the United States, outside of Alaska (Saunders et al. 2008). During the last five years, the West has experienced an increase in average temperature, compared to the 20th-century average, that is 70% greater than the world as a whole (Saunders et al. 2008). The average New Mexico summer is 3.4°F warmer now than in 1984. New Mexico summers are predicted to be hotter, dryer, and longer (Houser et al. 2015).

Climate warming is assured and does not bode well for the future status of *ciénagas*. The borderlands are going to get warmer, and minimum winter and maximum summer temperatures will increase in the Southwest. The severity and duration of drought and intensity of precipitation events will worsen, precipitation will decrease, and snowpack runoff will lessen and occur earlier, all of which will increase stress on *ciénagas* and wetland systems generally (Brunelle et al. 2010; Zeedyk et al. 2014). The Arctic is warming about twice as fast as the rest of the planet and heat-trapping greenhouse gas concentrations continue to rise, with the global average atmospheric concentration of carbon dioxide now more than 400 parts per million for the first time in human history (Houser et al. 2015). A recent analysis of climate change posits that the 2011 Texas and English heat waves were, respectively, 20 and 60 times more likely than they would have been 50 years earlier, because of climate change.

With climate change dramatically escalating and with the soaring frequency of extreme weather, *ciénaga* restoration and management will become increasingly difficult. The erosive force of more-intense storm events will increase the rate of degradation of unstable systems and decrease the likelihood and extent of restoration success (Zeedyk et al. 2014).

The forthcoming barrage of heat, droughts, and high-risk weather will occur in a context of a Southwest landscape already severely degraded, depleted of grasses and groundwater, and with ever-deepening incisions. Almost a century ago, Aldo Leopold forewarned us about the importance of restoration: “When the gullying and loss of bottom lands once starts, no system of range control, unaided by artificial works, can possibly check the process” (quoted in Meine and Knight 1999).

Add extreme weather events—more heat, less snow and rain, floods, droughts, and worse storms—on top of these existing conditions and it becomes clear that the task of recapturing stable *ciénaga* dynamics is a formidable one.

Summary of Benefits and Destructive Causes

The benefits provided by *ciénagas* to the aridlands of the Southwest are many. *Ciénagas* not only provide rich habitat for plant and animal life, they were also historically responsible for lateral spreading of flood pulses that wetted large swaths of land. This diffuse broadcasting of water resulted in abundant aboveground vegetation, thereby limiting the erosive potential of floods and protecting softer surface sediments. Broad *ciénaga* surfaces in floodplains dispersed seasonal flood pulses into sheet flows and prevented channelization. Floodplain *ciénagas* and grasslands formerly captured large amounts of sediment suspended in sheet flows that for the past 200 years have eroded barren soils and created today’s gully-washers, or heavy, fast, and destructive water (Minckley and Brunelle 2007). Rushing water now surges through ever-deepening incisions or arroyos throughout the Southwest. The result is heightened flash-flooding and exaggerated channel discharge that have reduced water tables and further worsened the already severe dewatering of *ciénagas* (Minckley and Brunelle 2007). The introduction of cattle and sheep, elimination of beaver and fire, agricultural recontouring, and drought have caused irreversible change.

The combination of the above forces had synergistic implications that transformed the entire Southwest, causing desertification that has drastically reduced *ciénagas* and extent of wetlands (Minckley et al. 2013). Review of the papers addressing *ciénagas* suggests the dominant land-surface process in the Southwest today is stream scour, which is the opposite of sheet flow, or slow-moving water, a phenomenon that was far more common just 200 years ago (Hendrickson and Minckley 1985). The current status of *ciénagas* is stark. Since the late 1800s, erosion associated with post-settlement channelization and drawdowns of local water tables have dried up most *ciénaga* environments to a mere 5% of historic *ciénaga* habitat (Fig. 5; Minckley and Brunelle 2007).



Fig. 5. Former San Simon Cienega on the Arizona/New Mexico border now dead, beyond any possible recovery despite a determined, long-range government effort, since abandoned. Photo: Cinda Cole (2010).

Ciénagas Developed Slowly over Eons

Unlike the short period of abrupt and rapid destructive forces that destroyed most ciénaga habitat, the mechanisms underlying their development about 11,500 years ago at the beginning of the last ice age were gradual (Minckley et al. 2009). Interwoven, multidisciplinary approaches drawn from botany, geology, geophysics, geography, and other disciplines are allowing the elusive ciénaga history to slowly be revealed. As summarized in Table 1, scientists are teasing out this history by investigating the record of soil buildup via sediment analysis of cores drawn from ciénagas. These cores contain stable sedimentary isotopes, pollen, microscopic charcoal or fire remnants, and elemental fractions of organic materials

that allow identification of the sources of the material buried within the sediments.

There are several summarizing conclusions that can be drawn from the chronology presented in Table 1: (1) Ciénagas developed gradually over 10 millennia, with only occasional spikes in their aggradation between 6000 BP (before present) and the arrival of Europeans in the Southwest; (2) European settlers immediately reduced fire incidence and put an end to tree or other woody-plant burning and started the trend in which trees outcompete grass, still ongoing today; and (3) weather factors, especially El Niño and La Niña events, are the primary drivers for fire occurrence and frequency in borderland desert grassland systems and are key to understanding the severe weather variability unique to the

Table 1. Timeline of Ciénaga Development. The time period Before the Present is abbreviated with “BP,” the Common Era often referred to as AD, is noted as “CE.”

21,000 BP	The period of the last glacial maximum. Ice sheets throughout the globe were at their maximum on Earth, glaciers were at their thickest, and sea levels at their lowest. The American deserts were forested, with the landscape punctuated by large pluvial lakes and flowing rivers (Minckley et al. 2009).
11,500 BP	Pleistocene Epoch ended and Holocene Epoch began. Stream flows remained strong, capable of moving rocks and cobbles, precluding establishment of most ciénagas, save those few along more protected reaches (Minckley et al. 2009).
8000 BP	To date, the oldest continuous evidence of ciénaga materials that allows inferences as to when and how ciénagas developed; water flows remained robust and thus prevented the wholesale establishment of ciénagas. This was a time when winter precipitation was minimal and fire was rare (Brunelle et al. 2010). However, there is evidence of ciénaga development in the International Four Corners Region into the last ice age (Minckley et al. 2012).
7200 BP	Initial stabilization of ciénagas as surface flows slowed, allowing formation of wetlands. Although there have been periods of rapid ciénaga development, during most of the past 7,000 years ciénagas have been slowly aggrading (Minckley and Brunelle 2007).
6000 BP	Onset of El Niño/La Niña–Southern Oscillation, with recurring, alternating, quasiperiodic warm and cool climate patterns that occur across the tropical Pacific Ocean and account for much of the fire variability in the Southwest (Brunelle et al. 2010).
5300 BP	Before this period, woody plants dominated the uplands, with fire-episode frequency below one fire every 200 years and even more infrequent when winter precipitation was low. The transition to grasslands began at approximately this time; after this period, fire frequency increased to 1.3 fires every 100 years (Brunelle et al. 2010).
7200–4100 BP	Fine-grain sediment increased, suggesting permanent and prolonged annual wetting. Stable ciénagas went through at least three steady states after initial stabilization: 6300–6000 BP, 4700–4000 BP, and 1600–750 BP.
4500 BP	Due to heavy moisture, a period of river system down-cutting in the Southwest. Fire frequency increased to one fire every 48 years (Brunelle et al. 2010).
4100–2400 BP	1,700-year dry interval period where ciénaga water permanence drastically lessened and fire frequency decreased to only one fire every 100 years (Brunelle et al. 2010).
4100–1300 BP	With the Southwest dominated by grasses, this period is similar to the present day. Ciénagas were stable, with the transitional shift from arid habitat to wetter conditions trending toward more aquatic states, conditions that persisted until European settlement (Brunelle et al. 2010).
3400 BP	Earliest presence of human activity is demonstrated by the presence of corn (<i>Zea</i>) pollen at Animas Creek Ciénaga in New Mexico. Corn pollen has been found in various sediment cores extracted from ciénagas throughout the region, establishing Native Americans’ use of ciénagas and their surroundings (Brunelle et al. 2010).

1300–750 BP	Stability in upland vegetation and ciénaga surfaces, water ponding and stagnation of the water likely occurring (Minckley et al. 2009). Sedges and cattails dominated and fire frequency increased to one every 38 years (Brunelle et al. 2010).
1680 CE	Pueblo Revolt expelled Spanish for 12 years until the reconquest in 1692 (Dunmire 2013).
1700s CE	Dramatic decline of charcoal corresponds with the appearance of pollen from a European plant, filaree (<i>Erodium cicutarium</i>). Sediment cores are dated to about 1795, which corresponds with establishment of Camp Grant in 1860, 200 years after Spanish recolonization in 1692. Coring shows frequent burning of some ciénagas before the arrival of Europeans. Six ciénagas record an increase in dung fungus (<i>Sporormiella</i>) spores common among grazing animals, in response to the introduction of livestock. This change in fire history is linked to human activity by the pre-settlement presence of the pollen of weeds and corn (<i>Zea</i>) in the ciénagas (Davis et al. 2002).
1800 CE	Before 1800, fire frequency had increased, on average, to one fire every decade, but abruptly decreased with the displacement of native agriculture by Euro-American settlement, triggering accelerated post-settlement transformation of wetland vegetation toward woody species (Brunelle et al. 2010).

Southwest. This extreme climatic variability overshadows all other factors influencing fire, vegetation, and ciénaga conditions (Brunelle et al. 2010).

The 1985 Call for Scientific Study of Ciénagas

The importance of ciénagas, the extent of their disappearance, and their ongoing damage were recognized only some 30 years ago by ichthyologists Hendrickson and Minckley (1985). They studied ciénagas in southeast Arizona and for the first time registered them on the academic radar. As a result of their summons for further study, current research has focused on diverse aspects of ciénagas, including their history; their vegetation composition; how and when they developed; the extent and causes of ciénaga losses; the impacts of climate change; and the means and potential for their restoration, conservation, and management (Minckley et al. 2012). Scientists are rapidly gaining an understanding of these unique wetlands of the arid Southwest.

Microscopic charcoal from six Sonoran Desert ciénagas in Arizona and Sonora, Mexico, documents a marked expansion of wetland taxa, particularly woody plants, about 200 years ago when Europeans arrived (Davis et al. 2002). These studies (Table 2) chronicle a series of abrupt changes in fire, vegetation, and sediment content during the transition from the periods before and after arrival of the Spanish, and summarize findings consistent with these changes (Davis et al. 2002; Minckley et al. 2009).

Recent studies have expanded upon Hendrickson and Minckley's (1985) work and convincingly demonstrated the increasing peril facing this unique aridland water (Minckley and Brunelle 2007; Minckley et al. 2009; Minckley et al. 2013). Spring ecosystems are among the most threatened ecosystems on Earth (Stevens and Meretsky 2008).

Table 2. Absence of fire in the Southwest upon arrival of Anglo-Europeans. Source: Davis et al. (2002), unless otherwise noted.

- Historic documents indicate frequent burning of southern Arizona vegetation by indigenous peoples.
- The historic reduction of fire frequency is a general conclusion of most tree-ring studies of fire frequency in the region.
- Before the turn of the century, desert wetlands were described as boggy, open environments with riparian gallery forests situated above the waterlogged soils of the valley bottoms (Minckley et al. 2009).
- The presence of charred seeds and fruits of wetland plants in pre-arrival sediment establishes burning of ciénagas.
- Before this transition, burning was frequent enough to exclude most woody plants.
- Prehistoric agricultural utilization of ciénagas is demonstrated by the presence of corn (*Zea*) and pre-Columbian weeds. The change in fire history is linked to human activity by the prehistoric presence of pollen of weeds and corn in the ciénagas.
- Borderland ciénagas show a marked expansion of the pollen of wetland taxa during the post-arrival period and these expansions follow or are accompanied by decreased charcoal abundance.
- The six Sonoran Desert sites studied by Davis appear to record increases in charcoal percentages up to the time of the abrupt fire decline. This fall-off in sediment charcoal indicates a dramatic decrease in fire frequency in the period after European arrival.
- Reduced fire frequency caused the historic transformation of wetland vegetation in the Sonoran Desert to woody plants.

The Extent of Ciénagas

Partial ciénaga inventories presented in scientific literature offer differing definitions and terms to describe and categorize ciénagas. Some writers list only functioning ciénagas (Sivinski and Tonne 2011), while others include a far broader range of ciénaga conditions (Housman 2010). Other researchers limit their treatment of ciénagas to certain regions of the Southwest, excluding those outside their geographic range of interest (Hendrickson and Minckley 1985; Minckley et al. 2013). Additionally, there are researchers who include wetlands above a certain altitude (Minckley et al. 2013), while others exclude them, rather defining them as “high mountain meadows” (Sivinski and Tonne 2011). These differences typically reflect the scope or purpose of the research, although these differences have muddled the understanding of ciénagas as recent research has heightened appreciation of their importance. Because of ciénaga scholarship’s relative newness, varying research purposes, and differing criteria used to describe ciénagas, it is difficult to reconcile available data in order to answer questions about their numbers, extent, and condition.

Prior to European settlement, there were likely hundreds of overlooked or forgotten ciénagas—unnoticed or unnamed—with the result that, at elevations below 2,133 m (7,000 ft), only 155 identified ciénagas are known to currently exist in the entire International Four Corners Region of the Southwest—Arizona, Sonora, New Mexico, and Chihuahua—along with several outliers in west Texas (Fig. 6). Tom Minckley (pers. comm. 2012) speculates that there may be well over 200 ciénagas, not the 155 that are listed (Fig. 6; Appendix B). Dean Hendrickson (pers. comm. 2014) suggests that there are hundreds if not thousands of ciénagas undocumented across the West. As awareness of their importance increases, so will the number of identified ciénagas. There are also named ciénagas that can no longer be located and an unknown number of scattered ciénagas existing on private land but held secret because landowners fear that detection will adversely affect their property rights.

All ciénagas known to us are described in Appendix B and mapped in Figure 6. Of the 155 we have identified, 87 (56%) are either dead or so severely compromised that there is no prospect for their restoration. We believe 40 (26%) remain functional and 28 (12%) are restorable. Because this

paper is intended as a working inventory of known ciénagas, we have included in Appendix B seven additional ciénaga-like waters found above 2,100 m (7,000 ft), but these are outside the scope of this paper and are included for reference only. See Appendix C for additional water sources that can be found along and nearby historic travel routes, many of which were, at one time, likely ciénagas.

It is critical to keep in mind that a simple numerical count of ciénaga losses seriously understates the extent of ciénaga habitat loss. Most ciénagas that still have perennial water are severely incised and retain but a thin slice of their historic width (Figs. 1–3). Hendrickson and Minckley (1985) estimated habitat loss of ciénagas to be upwards of 95%, a figure commonly reported in the literature (Makings 2013). In the editor’s introductory note to Hendrickson and Minckley (1985), Crosswhite stated that ciénaga locations were among the most mistreated sites on Earth. As an illustration of this point, Figure 3 makes clear that the reach of the Burro Ciénaga on the Pitchfork Ranch is less than 5% the width that existed before settlers recontoured the valley.

A Proposed Classification System for Ciénagas

Proposed here is a ciénaga classification system based on current function, stability, and restorability. This is a meaningful way to identify, evaluate, and prioritize those ciénagas

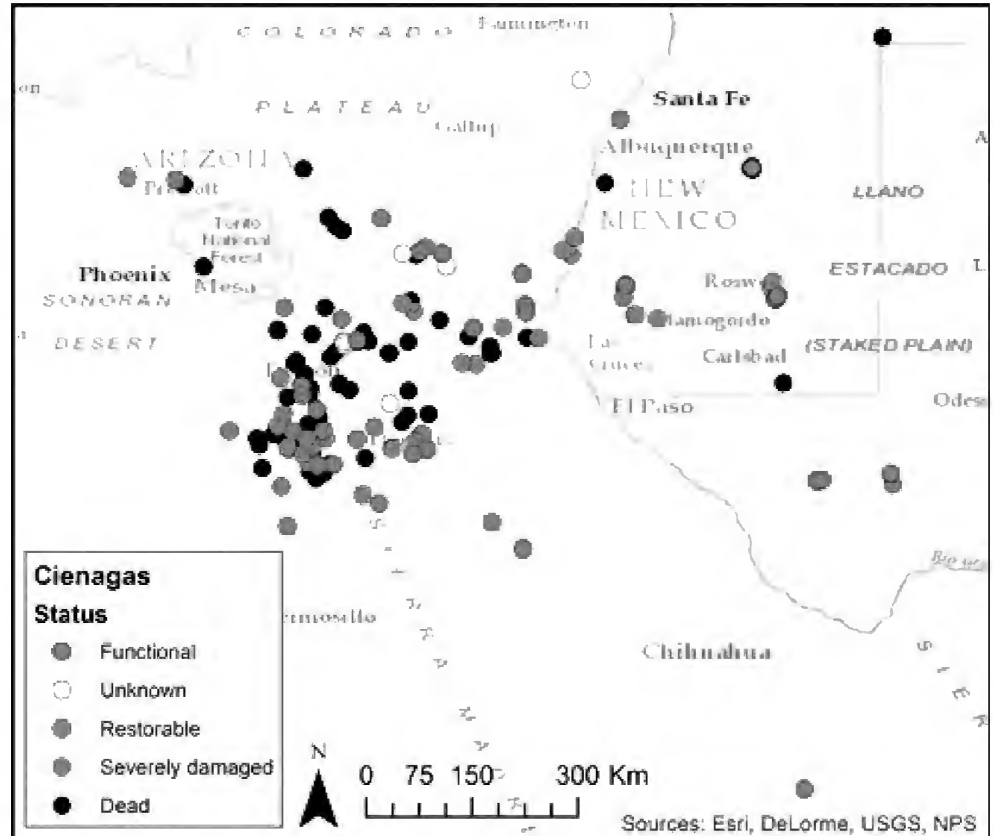


Fig. 6. Ciénaga locations in the International Four Corners Region. Map: Ben Labay, Ichthyology Collection, Integrative Biology, University of Texas, Austin (2015).

that can be restored and where agencies and landowners can best invest limited capital. The four categories presented take into account what was; what is; and what could be if *ciénagas* were recognized, prioritized, and restored.

1. Functioning *Ciénagas*. These are *ciénagas* whose structure and function are essentially unimpaired: not seriously incised, often broad and marshy, functioning much as they did before Spanish and Anglo settlement. However, most of these are markedly reduced in size. A mere 26% ($N = 40$ total) of *ciénagas* listed in Appendix B remain intact, and their rarity mandates high-priority management and preservation (Figs. 7 and 8).



Fig. 7. Cloverdale Cienega, Bootheel region of southwest New Mexico. This is what an essentially undamaged *ciénaga* looks like. Photo: Thomas A. Minckley (2008).



Fig. 8. Cieneguita, Las Cienegas, north of Sonoita, Arizona. With almost no incising, this is a smaller, functioning *ciénaga*. Photo: Karla Sartor (2012).

2. Restorable *Ciénagas*. These *ciénagas* still have perennial water and abundant *ciénaga* flora in their marshy reaches, but in other stretches are dry or function like creeks. They are deteriorating toward a drained state but remain in a semihealthy condition and are ideal candidates for restoration. These *ciénagas* have potential to be restored to fully functioning status. They make up about 18% ($N = 28$) of all *ciénagas* documented in Appendix B (Figures 1–3).

3. Severely Damaged *Ciénagas*. These are ephemeral, periodically wetted by rains. They have questionable restoration potential and make up just over 12% ($N = 18$) of *ciénagas* listed in Appendix B.

4. Dead *Ciénagas*. At least 44% ($N = 69$) of *ciénagas* included in Appendix B are dead, their water tables so severely depleted that restoration, given water tables and today's techniques and economics, is not feasible (Fig. 4).

Were there a greater number of *ciénagas* in the Southwest before Spanish sheepherders, American trappers, and the other causes of the Southwest's dewatering? Definitely. Were there hundreds more? Probably, but there are some who disagree and the answer will likely never be known. At one time, there were springs along the travel routes noted in Appendix C. Most of them no longer exist, and of those, there surely were some that supported unnoticed or undocumented *ciénagas*. Are there other existing *ciénagas* not on this list? Certainly, we know of some now. Will other *ciénagas* be added to this list? Surely; we just added one. Are there more than two dozen restorable *ciénagas*? After our experience in the ongoing task of restoring the reach of the Burro Cienega on the Pitchfork Ranch, we suspect not. Yet there are those who see this differently too. Is there uncertainty and more to learn about *ciénagas*? Yes, for sure. Is there any habitat restoration in the Southwest more important? We think not, and we doubt that many people, once fully informed, will disagree.

A Proposal for Restoration and Preservation

Desert wetlands have long been overlooked in conservation-priority assessments and yet have exceptional value for avian diversity, as historic riparian sites in the Southwest lessen in number and more species of migrating birds use isolated *ciénagas* (Minckley et al. 2013). The conservation potential for *ciénagas* in arid and semi-arid ecosystems is incredibly high, considering the wealth of ecosystem services these environments provide when functioning properly. Their conservation value will increase under the conditions expected with global climate change.

Given the challenges of how to best spend limited conservation dollars and resources, conservation and restoration of extant *ciénagas* may prove to yield the greatest net benefit to counter current endangerment (Minckley et al. 2013).

As the inventory of *ciénagas* in Appendix B shows, few remain and many are damaged beyond repair. We note location by state and condition in Table 3. These numbers demonstrate that 87 (56%) of all aridland *ciénagas* known to exist are beyond repair and only 68 (44%) are suitable for preservation and restoration. Yet even these disheartening numbers are starkly deceptive, because 95% of all *ciénaga* habitats have been lost. The importance of *ciénagas* warrants a far more concerted restoration and preservation undertaking than the current unfocused effort.

We propose that the New Mexico Department of Game and Fish, the Arizona Game and Fish Department, and corresponding entities in the Mexican states of Sonora and Chihuahua collaborate to create the position of *Ciénaga Coordinator* so that the four states can work together to develop a program of restoration priorities and outreach to owners of *ciénagas*, both public and private, and thus begin a formalized region-wide process of ensuring the persistence of *ciénagas* in the International Four Corners Region. These coordinators' charge should entail not only identification and prioritization of *ciénaga* restoration, but extend to:

- Collaborating with owners
- Identifying restoration and funding sources
- Providing assistance in seeking funds
- Arranging or recommending restoration personnel
- Overseeing restoration activities when requested
- Periodically conducting site visits with the goal of helping owners ensure their *ciénagas*' long-range care
- Exploring the option of conserving *ciénagas* with protective fencing
- Recommending, when appropriate, optional conservation easements and other preservation measures

Table 3. Known *ciénagas* occurring at elevations below 2,133 m (7,000 ft) by state, functional condition, proportion of total, and total percent. Fewer than half (44%) of known *ciénagas* are functional and/or restorable, while 56% have no potential for restoration or are dead.

Total Number	Condition (total N by category)	Condition as percent of total
67 (Arizona, USA)	Functional (39)	25%
60 (New Mexico, USA)	Restorable (29)	19%
4 (Texas, USA)	Severely Damaged (18)	12%
1 (Coahuila, MX)	Dead (69)	44%
20 (Sonora, MX)		
3 (Chihuahua, MX)		
155 (Total)	155	100%

Depending on the extent of damage, the depth of incision, and related factors, the restoration process can be costly and extend over many years, emphasizing the need for *Ciénaga Coordinators*. Many private landowners do not fully appreciate the importance of *ciénagas* and few can afford the cost of what, for us, projects to be a more than two-decade process. Except in the most exceptional cases, public funding is necessary.

In view of the ecosystem services that *ciénagas* provide and their importance in providing habitat for endangered, at-risk species and wildlife in general, various scholars have already stated that no habitats in the Southwest are more important to restore (Minckley et al. 2012). The carbon sequestration potential of wetlands adds yet another benefit of prioritizing *ciénaga* restoration (White 2014; Ohlson 2014). The highest rate of return, the most benefit per dollar of public funds invested in *ciénaga* restoration, underscores this call for *Ciénaga Coordinators*.

Zeedyk and Clothier (2009) have detailed an evolving template for restoring incised channels in the arid Southwest and acknowledged that additional practices would likely be developed. Indeed, after a decade of restoring the portion of the Burro Ciénaga on the Pitchfork Ranch, we have happened upon several other types of grade-control structures, incorporated in Zeedyk and colleagues (2014). A concerted focus on these unique desert habitats should lead to an increased emphasis on restoration and preservation strategies.

The Ethical Imperative for Restoration

Rapid degradation of the landscape across the nation was Aldo Leopold's abiding concern and brought him to confront the universality of challenges facing the protection of important habitat: "The government cannot buy 'everywhere' . . . The private landowner *must* enter the picture . . . The basic problem is to induce the private landowner to conserve his own land, and no conceivable millions or billions for public land purchase can alter that fact, nor the fact that so far he hasn't done it" (quoted in Meine and Knight 1999, 162; emphasis in original). Although these endangered habitats have suffered rapid change and a staggering number of losses, the few remaining *ciénagas* are salvageable, beneficial, and even profitable if restored, but private landowner participation is essential.

Widespread spontaneous recovery of *ciénagas* is unlikely without concerted restoration efforts. *Ciénagas* will self-heal only in small areas where local geomorphic structure is particularly favorable to wetland development (Heffernan 2008). Once established, *ciénaga* vegetation appears highly resistant to removal by seasonal flooding, has a stabilizing effect on the streambed, and thus becomes a sink for sediment trapping and water retention (Minckley et al. 2012). The dramatic change evident in the photographs in Figure 4 demonstrates how quickly *ciénagas* and riparian habitat respond to restoration. Carbon sinks are wetlands that are highly efficient in capturing carbon, and, although recent publications addressing this question of carbon sequestration neglect to mention

ciénagas, we suggest that ciénagas serve as ideal carbon sinks, of which there are so few in the Southwest (Schwartz 2013; White 2014; Ohlson 2014).

Widescale recovery of ciénagas will require a significant shift in awareness among the general public, rethinking by bureaucrats, and a much-needed broadening of the current political ethic to emphasize land, water, and habitat restoration in order to return these aridland waters to their natural state.

Conclusion

Everyone—politicians, agency personnel, scholars, and land managers and owners—is interested in a return on investment. The persistent question is where to best spend limited funds. In Arizona, as of 2012, there were 82 plants or animals considered to be endangered, threatened, or proposed for listing under the federal Endangered Species Act. Of these, 16 are directly associated with ciénagas (Minckley et al. 2013). Aridland springs and ciénagas provide vastly disproportionate benefits to regional ecology, evolutionary processes, and sociocultural economics in relation to their size and number (Stevens and Meretsky 2008). We know from our own experience at the Pitchfork Ranch that there are only limited funds available for ciénaga restoration and habitat improvement. If funders and restoration practitioners expect to meaningfully help at-risk plants and animals, and contend with climate change, investing in ciénaga restoration can help.

More than all other habitat types, ciénagas have the potential to represent a great success story in conservation, given that the degradation of these systems is relatively recent and that ciénagas have remarkable resilience once disturbance pressures are removed (Minckley et al. 2012; Minckley et al. 2013). Despite the troubling number and scope of losses and severe damage to the few ciénagas that remain, there are still a good number that have long persisted and these arguably represent the most important resource for the maintenance and preservation of regional biodiversity.

A fundamental tenet of citizenship in the West is to translate Leopold's Land Ethic into reality. There are few opportunities with more potential and greater rewards than the restoration of the remaining ciénagas in the International Four Corners Region. The creation of Ciénaga Coordinators and adoption of a classification system based on their present condition and potential for restoration will help determine which of the remaining ciénagas are within reach of being turned in the direction of their presettlement condition.

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Appendix A. Ciénaga Spelling and Punctuation

The *Real Academia Española* has this to say about spelling: The term *ciénaga* is derived from Latin *caenīca*, *caenum*, *ciēno*; and *ciénaga* is derived from the single word *ciénega*. One theory for the word *ciénaga* is that it derives from the expression *cién aguas*, meaning “a hundred fountains,” “a hundred springs,” or “100 waters” (Hendrickson and Minckley 1985), but, linguistically, the term has nothing to do with either water or hundred. Although the origin of *ciénega* and its variant *ciénaga* is not a simple one, the root is “silt,” which is the meaning of *cieno*. The origin of what can only be considered a colloquial definition—100 waters—is unknown to us, but it is a sensible definition and explanation for spelling *ciénaga* the less common way in the American Southwest. Other enclaves in the Spanish-speaking world (e.g., Colombia) utilize the word in the formal names of many swamps and bogs, and the second-*e* spelling is rare. But spelling *ciénaga* with a *i* is less common elsewhere in the Spanish-speaking world.

Julyan (1996) notes that although the *e* spelling had been earlier criticized, many early Spanish explorers and settlers came from Extremadura, Spain, where *ciénega* was properly spelled with a second *e*. Pearce (1965) lists 14 New Mexico examples of *ciénaga* usage—land grants, towns, and water features—and they are all spelled with an *a* and no accent mark over the first *e*. Pearce’s book preceded Julyan’s by 25 years and uniformly uses the *a* spelling, making no mention of spelling *ciénaga* with a second *e*.

A close examination of these books makes apparent that Julyan used numerous examples from Pearce and substituted the second *e* for *a* without explanation. Two examples are Pearce’s entries for *Cienaga (Otero)* and *Cienaga (Catron)* (p. 35). Pearce spells the *ciénagas* in Otero and Catron counties

with the *a* yet Julyan (p. 84), without comment, substitutes an *e*. The thinking behind the Pearce/Julyan substitution is unknown, and it is also unclear when and why the *e* spelling as represented by Julyan as “general” became so commonly accepted in the Southwest. One explanation for the more common *e* spelling today is that when Hendrickson and Minckley (1985) first suffused the term *ciénaga* with the biological significance unique to the groundwater-fed aridland *ciénagas* of the American Southwest, they chose the *e* spelling, and it has persisted in the scientific literature.

Neither spelling is corrupted, although the spelling *ciénega*, using the second *e* and no accent, has indeed become common in the United States in scientific, if not popular, usage. The spelling with a second *e* is common on many, but not all, contemporary maps. The colloquial explanation—linguistically incorrect—of “*cien-aguas*” or “100-waters,” with *agua* containing a *a* rather than an *e*, does lend a commonsense suggestion for the less common spelling.

The accent mark over the first (or only) *e* is proper, although often omitted.

Appendix B. Working Ciénaga Inventory

In this appendix, we present a list of known *ciénegas* located in the International Four Corners Region (Arizona, New Mexico, Sonora, and Chihuahua) and a very few outliers in neighboring states. Our reasoning for labeling this list a “Working Ciénaga Inventory” is because *ciénaga* numbers may forever remain uncertain, any inventory will likely be incomplete, and additions are inevitable.

Those working with these unique aridland water features understand that there are other *ciénagas* neither noticed nor named and no longer wet, others that are known but in the hands of private owners who prefer to remain off the radar, still others that are mentioned in older reports and overlooked studies, and even more than a few not yet discovered, often known to locals but of little interest. Readers are encouraged to build on this initial effort to identify all known *ciénagas*. If you learn of an unlisted *ciénaga*, or are able to identify elevation, latitude/longitude and present status for any listed *ciénaga* in this inventory where information is lacking, please notify us:

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Confusion also surrounds the application of the word *ciénaga* to an entire watercourse, such as the Burro Cienaga, where an 8.4 km (5 mi) reach of the 76.60 km (47.6 mi) Burro Cienaga watercourse was likely never authentic *ciénaga*. Yet there is a 2.27 ha (5.6 ac) archaeological site adjacent to the Burro Cienaga on the southern portion of the Pitchfork Ranch that was occupied by the Mimbres people over a 400-year period between 700 CE and 1100 CE, suggesting the

presence of perennial water. We also found 11,000-year-old Archaic points adjacent to the Burro Cienaga on the north portion of the ranch, making the history of the watercourse rich, but difficult to uncover.

Further confusion surrounds application of the term to former *ciénagas* that are now desiccated (dewatered), non-living, or “dead.” We continue to apply the term when referring to dead *ciénagas* because inclusion of all *ciénagas* sheds light on the fact that their numbers were already limited even before the arrival of Europeans and are steadily decreasing today. In addition to springs that may at one time have supported *ciénaga* habitat, there have been several dozen more named *ciénagas* (some are excluded here as “high mountain meadows”) that do not appear on lists presented in various *ciénaga* papers. Of course, there are even more *ciénagas* that have passed into oblivion as groundwater levels have dropped, as well as those that were unnoticed, unnamed, and never documented.

Next, consideration must be given to the upper range of “elevation” when defining a *ciénaga*. One of the earliest *ciénaga* elevation ranges applied the term to mid-elevation (1,000–2,000 m; 3,281–6,566 ft) wetlands characterized by “permanently saturated, highly organic, anaerobic soils” (Hendrickson and Minkley 1985). Other studies have extended the elevation to 2,133 m (7,000 ft) (Sivinski and Tonne 2011). Still others have applied the term to spring-fed habitats over 3,048 m (10,000 ft) (Minckley et al. 2012). However, we feel it is best to refer to spring-fed waters at high elevations as “wet mountain meadows” rather than as *ciénagas*, to avoid diluting the core attributes of *ciénagas*: often spring-fed, marshy aridland habitat, occurring at elevations below 2,133 m (7,000 ft).

There are also those who understand an earlier, everyday use of the term *ciénaga* that simply means a “wet spot”; permanent water was not necessarily implied by use of the term. While such usage may have enjoyed currency, those “intermittent” water features should not be thought of as *ciénagas*. Occasional waters are not included here, but rather the well-accepted and narrower definition that considers perennial water as the appropriate criterion and is in keeping with the current, universally accepted use of the term. Authentic *ciénaga* plants—sedges, rushes, and reeds—will not persist in the absence of perennial water. Water features such as (1) springs without *ciénaga* plants, (2) *sumideros* (masked sinkholes), (3) high mountain meadows, and (4) “wet spots” are not true *ciénagas* and are excluded from this working inventory.

There is an assortment of diverse usages or styles for the word *ciénaga* found on various maps. For example, the Burro Cienega is spelled with a second *e* on the 1884 Powell and Kingman map, but with an *a* on the USDI Geological Survey Werney Hill Quadrangle (Geological Survey, 1963) and various other maps, including modern computer-based mapping systems such as the current DeLorme (2006) map. In keeping with the diverse naming of early Southwest water features, the spring or *ojo* along the Burro Cienaga was initially named *Ojo de Inez* by John Russell in 1851 (Bartlett

1965). It is noted as such on Lieut. Wheeler’s 1873 expedition map (Eidenbach 2012) and labeled *Ojo de la Inez* on the Captain Allen Anderson 1864 *Map of the Military Department of New Mexico* (Eidenbach 2012), yet the 1884 Powell and Kingman map (Powell & Kingman 1884), uses *Burro Cienega Springs* with an *s*, implying multiple springs as noted initially by Bartlett when he was conducting the post–Mexican War boundary survey. More recent and all current maps refer to the now-singular spring as Cienaga Spring.

The single most uncertain aspect of *ciénagas* is their numbers. Estimates vary, but seldom exceed 200. The list presented here is thought to be the most comprehensive published inventory to date and identifies only 155 *ciénagas*. After examining older maps and realizing what a large number of springs (*ojos*) are no longer wet, knowing the number of today’s springs that support *ciénagas*, and knowing that most *ciénagas* are associated with springs, it seems likely that there were hundreds more *ciénagas* in the past that were never documented.

The number or percentages of *ciénagas* can be deceptive. There were likely *ciénagas* associated with springs noted in Appendix C that are excluded from these numbers, and others that were simply unnoticed or already dewatered when the maps were made. Most importantly, the size of those remaining *ciénagas* is greatly reduced, as they are typically severely incised and present more “creek-like” than marsh-like habitat. There is a critical difference between the remaining *numbers* of *ciénagas* and the remaining *acreage* of those *ciénagas* that are still functional or restorable. While 46% of *ciénaga* numbers may remain wet, over 95% of historic *ciénaga* acreage is dry. The combined percentages below indicate that 87 *ciénagas* (55%) are dead or so severely damaged as to be beyond repair, leaving only 127 *ciénagas* (46%) either functioning or restorable.

1. **Functioning Ciénagas. (F)** These are *ciénagas* whose structure and function are essentially unimpaired: not seriously incised, broad and marshy, with *ciénaga* vegetation, functioning much as they did before European contact. These *ciénagas* remain intact and their rarity mandates high-priority management and preservation.
2. **Restorable Ciénagas. (R)** These *ciénagas* still have perennial water and abundant *ciénaga* plants in their marshy reaches but in other stretches are dry or function more like creeks. They are deteriorating toward a drained state but remain in a semi-healthy condition and are ideal candidates for restoration. These *ciénagas* have the potential to be restored to functioning *ciénagas*.
3. **Severely Damaged Ciénagas. (S)** These are ephemeral, periodically wetted by rains, with no *ciénaga* vegetation. We believe they have little restoration potential.
4. **Dead Ciénagas. (D)** This is the largest category. Dead *ciénagas* have water tables so severely depleted that restoration, given current water tables and today’s techniques and economics, is not feasible.

The known *ciénagas* inventoried here have been identified from the named sources, along with the year we understand

the ciénaga first appeared on a written list (without regard to a map) or was brought to our attention. In some instances, data are lacking and it is our hope that the reader will contact us with additional information to compile a more thorough working inventory. It must be noted that in many cases these data have not been ground-truthed. We have relied upon aerial and satellite data to verify the current, or most recent, condition of a given ciénaga, as well as the current location of some ciénegas.

Following the name of each ciénaga, we give the state in which it occurs as follows: AZ = Arizona, USA; CH = Chihuahua, Mexico; NM = New Mexico, USA; SO = Sonora, Mexico; TX = Texas, USA; CO = Coahuila, Mexico. Latitude and longitude follow the ciénaga name for ease of pasting into the Search bar on Google Earth (datum WGS84). Note that some coordinates were collected in an unknown datum so that locations must be considered accurate, but not precise.

These data are also being made available online in an interactive open format for comments and other contributions. Anyone interested in contributing to the correction, evolution, and general improvement and growth of this database, or in using these data for their own research, can do so by going to the permanent archive of this paper at <http://hdl.handle.net/2152/30285> and following the link to an interactive site where the data can be mapped, and comments and new records submitted. This site is maintained and moderated by Dean Hendrickson (University of Texas) and Tom Minckley (University of Wyoming).

1. Agua Caliente Ciénaga (also known as: Pantano). Minckley et al. (2012). Mexico, Sonora, Nacozari de García municipio. Aquatic ecoregion (river basin)—Sonora. Coordinates: 30.64062 -109.4248; 934 m (3,065 ft) elevation. Appears to be a living ciénaga. A very rare plant has been found here: Arizona eryngo (*Eryngium sparganophyllum*). **S**
2. Alamosa Springs Ciénaga (also known as: Ojo Caliente). Sivinski and Tonne (2011). United States, New Mexico, Socorro County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 33.57258 -107.60042; 1,893 m (6,210 ft) elevation. Located in the southwest corner of Socorro County, NM, 24.1 km northwest of Monticello, this ciénaga is a complex of springs, seeps, and spring runs, some warm. These springs are at the heart of the Warm Springs Apache Tribe, where Apache warrior and seer Geronimo was captured for a short time in 1877 before he escaped. This ciénaga has a population of the endangered Chiricahua leopard frog (*Rana chiricahuensis*) and is the only known habitat for the endangered Alamosa springtail (*Tryonsia alamosa*). **F**
3. Animas Ciénaga. Housman (2010) and Minckley and Brunelle (2007). United States, New Mexico, Hidalgo County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.782571 -108.790884; 1,421 m (4,662 ft) elevation. Southeast of Rodeo, Hidalgo County, NM, this point is now a dry part of Animas Creek south of

the town of Animas that once was, but no longer is, a ciénaga. **D**

4. Animas Ciénaga. Minckley et al. (2012). United States, New Mexico, Hidalgo County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.527000 -108.884; 1,554 m (5,100 ft) elevation. This former ciénaga was located between the Guadalupe Mountains and Animas Mountains in Hidalgo County, NM. This was the Clanton Canyon arm of the Animas Ciénaga, now almost entirely converted to impoundments and riparian woodland and no longer a functional ciénaga. **D**
5. Animas Creek Ciénaga. Minckley et al. (2012). United States, New Mexico, Hidalgo County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.528000 -108.873; 1,563 m (5,127 ft) elevation. Although severely damaged, this ciénaga has several active surface spring seeps. **R**
6. Apache Tejo Spring. Sivinski, Robert, pers. comm. (2014). United States, New Mexico, Grant County. Aquatic ecoregion (river basin)—Guzman—Samalayuca. Coordinates: 32.6446 -108.0097; 1,678 m (5,504 ft) elevation. This is a dead ciénaga, per Sivinski, dewatered because of the nearby Hurley, NM copper mill. (Sivinski, pers. comm., 2014). **D**
7. Apache Creek Ciénaga. Sivinski, Robert, pers. comm. (2013). United States, New Mexico, Catron County. Aquatic ecoregion (river basin)—Gila. Coordinates: 33.8332 -108.6211; 1,957 m (6,422 ft) elevation. Located southwest of Socorro in Catron County, this is a functioning ciénaga. **F**
8. Arivaca Ciénaga. Housman (2010). United States, Arizona, Pima County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.571677 -111.325603; 1,106 m (3,630 ft) elevation. This ciénaga is just south of Arivaca, Pima County, AZ, north of Sonora. This ciénaga is fenced from livestock and with trails through the wet portions, is located to the west of these coordinates. **F**
9. Artesia Ciénaga. Hendrickson and Minckley (1985). United States, Arizona, Graham County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.700000 -109.7; 993 m (3,258 ft) elevation. Located south of Saford, AZ and Swift Trail Junction, there is no ciénaga at this point, only dry barren wetland soils to the north. **D**
10. Babocomari Ranch Ciénaga. Hendrickson, Dean A., pers. comm. (2015). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.631062 -110.451397; 1,390 m (4,557 ft) elevation. Located 7.7 km (4.8 mi) SE of Elgin, a small impoundment with marsh vegetation above a valley of riparian woodland and wet meadows. **F**
11. Babocomari River. Sivinski, Robert, pers. comm. (2014). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.650000 -110.33; 1,245 m (4,085 ft) elevation. East of Huachuca City, a 4-mile stretch of Babocomari used to have more permanent flow with small areas of wet meadow along the banks (Noonan, 2015, <http://sciencequest.webplus>).

net/Fairbank%20Cienego%20for%20web%20Final.pdf). It is presumably intermittent and the *ciénaga* is now dead.

D

12. Balmorhea *Ciénaga*. Hendrickson, Dean A. pers. comm. (2014). United States, Texas, Reeves County. Aquatic ecoregion (river basin)—Pecos. Coordinates: 30.944 -103.7861; 1,012 m (3,320 ft) elevation. Known at one time as Mescalero Springs for the Mescalero Apache who watered their horses there, this deep *ciénaga* is fed by San Solomon Springs and has been the site of human gatherings for at least 11,000 years. Now part of the Balmorhea State Park, more than 56,781 m³ (14,999,953 gal) of water flow through a giant swimming pool each day, where it thereafter enters irrigation canals for farmers and travels about 5.6 km (3.5 mi) east to Balmorhea Lake. Concrete encased and commercialized beyond measure, this precious aridland water is far from a natural *ciénaga* habitat, yet may contain more “live” water than any of the remaining *ciénagas*. The outlet, before supplying agriculture, passes through a restored *ciénaga* in which the native fish community and invertebrates flourish. **F**
13. Barrel Spring *Ciénaga*. Sivinski and Tonne (2011). United States, New Mexico, Otero County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 33.0558 -106.1606; 1,256 m (4,120 ft) elevation. Located west of Alamogordo, NM, Barrel Spring is a small, severely impacted, dredged spillway cut for impoundment. **S**
14. Batte Way *Ciénaga*. Sivinski and Tonne (2011). United States, New Mexico, Otero County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 33.0076 -105.8709; 1,737 m (5,700 ft) elevation. Located northeast of Alamogordo, this 70 x 30 m *ciénaga* is severely grazed and damaged by a road cut, although it persists due to being wetted by a small seep spring. **R**
15. Bingham *Ciénaga*. Sivinski, Robert, pers. comm. (2014). United States, Arizona, Pima County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.465699 -110.485519; 855 m (2,806 ft) elevation. Located northeast of Tucson in the corner of Pima County, a large tree now marks the former site of severely damaged Bingham *Cienaga*. Bingham *Cienaga* is managed by The Nature Conservancy who attempted 23 acres of wetland restoration of this *ciénaga* in the 1990s. The *ciénaga* has been mostly dry since 2003 because of drought and groundwater depletion (Davis 2012). Restoration of this *ciénaga* may ultimately need recovery of groundwater levels in the central San Pedro River valley. **R**
16. Bitter Lake Farm *Ciénaga*. Sivinski and Tonne (2011). United States, New Mexico, Chaves County. Aquatic ecoregion (river basin)—Pecos. Coordinates: 33.3837 -104.4214; 1,059 m (3,474 ft) elevation. The upper portion of this spring *ciénaga* habitat is small, and though the up-slope portion is intact, the lower portion is severely impacted by dikes, impoundments, and salt cedar (*Tamarix* sp.). **S**
17. Bitter Lake National Wildlife Refuge. Sivinski and Tonne (2011). United States, New Mexico, Chaves County. Aquatic ecoregion (river basin)—Pecos. Coordinates: 33.4619 -104.4014; 1,068 m (3,504 ft) elevation. Containing 227 ha (560 ac) of remnant natural *ciénaga* habitat, this complex cluster of former sinkholes, lakes, resurgent creeks, spring runs, and seeps used to be one of the largest areas of aridland spring *ciénagas* in the Southwest, and although damaged, according to Sivinski and Tonne (2011, 42) it continues to support the greatest biological diversity of any *ciénaga* in New Mexico. **R**
18. Blue Spring *Ciénaga*. Sivinski, Robert, pers. comm. (2014). United States, New Mexico, Eddy County. Aquatic ecoregion (river basin)—Pecos. Coordinates: 32.1803 -104.273; 1,000 m (3,282 ft) elevation. East of New Mexico’s Carlsbad Caverns, this *ciénaga* appears to have been excavated into a large stock tank. **D**
19. Bog Hole *Ciénaga*. Minckley et al. (2012). United States, Arizona, Santa Cruz County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.47 -110.62; 1,526 m (5,008 ft) elevation. Located southeast of Patagonia and northeast of Nogales, AZ at the headwaters of the Santa Cruz River, this *ciénaga* has been excavated into a large stock tank. **D**
20. Burro *Ciénaga* (also known as: Hawk Spring, Ojo de Inez, *Cienaga* Spring). USGS Topo Quad—Lordsburg, NM (2010). United States, New Mexico, Grant County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.4343 -108.3652; 1,631 m (5,351 ft) elevation. South of Silver City, NM, this is the severely incised 3.2 km-long portion of a live *ciénaga* on the Pitchfork Ranch currently undergoing restoration. Found along this incised waterway is *Cienaga* Spring, earlier named Ojo de Inez by John Russell Bartlett in 1851 (Bartlett, 1965) when it was “discovered” (by an Anglo). Describing a portion of what is now the Pitchfork Ranch: “The valley of the cañon leading to the Ojo de Inez ran up northwest, and was about 230 m wide near the spring or water-pool” (Report of Explorations and Surveys 1857). The federal- and state-listed Gila topminnow (*Poeciliopsis occidentalis*), Chiricahua leopard frog (*Rana chiricahuensis*), and Wright’s marsh thistle (*Cirsium wrightii*) have been reintroduced in this *ciénaga*. The obligate wetland species cardinal flower (*Lobelia cardinalis*) was discovered in the *ciénaga* in 2013. **R**
21. Bylas Spring (also known as: Geronimo-Bylas and Bylas Salt Spring). Minckley et al. (2012). United States, Arizona, Graham County. Aquatic ecoregion (river basin)—Gila. Coordinates: 33.16468 -110.114103; 806 m (2,643 ft) elevation. Formerly located southeast of Globe, AZ, east of Bylas, there is no longer any indication of a *ciénaga* at this location, which is now a floodplain. **D**
22. Canelo Hills *Ciénaga*. Sartor, Karla, pers. comm. (2013). United States, Arizona, Santa Cruz County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.560000 -110.526696; 1,508 m (4,946 ft) elevation. Located

- just short of 11 km directly south of Elgin, AZ, this is a broad marshy area with a clear stream bubbling up in the middle and running through it. This *ciénaga* is referred to as O'Donnell Creek basin by Hendrickson and Minckley (1985). There is a little more of the same *ciénaga* at 31.55 -110.52, elev. 1,521 m. **F**
23. Cascabel San Pedro *Ciénaga*. Hendrickson and Minckley (1985). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.29 -110.37; 963 m (3,161 ft) elevation. Located east of Tucson and east of Cascabel, Cochise County, AZ, there is no longer a *ciénaga* at this location. **D**
 24. Centerfire Bog. Sivinski, Robert, pers. comm. (2013). United States, New Mexico, Catron County. Aquatic ecoregion (river basin)—Gila. Coordinates: 33.9118 -108.8347; 2,179 m (7,150 ft) elevation. Located about 5 mi northeast of Hulsey Cienaga, several waters occur along this channel. **F**
 25. *Ciénaga Bercelo* (also known as: *Ciénaga los Nietos*). Minckley et al. (2012). Mexico, Sonora, Cananea municipio. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.0226 -110.1355; 1,462 m (4,795 ft) elevation. Located southwest of Douglas, AZ, and northeast of Cananea, Sonora, a creek remains at this location, but the *ciénaga* has been converted to cropland and a dam impoundment. **D**
 26. *Ciénaga Bonita* (also known as: Witlocks Cienaga). (Eidenbach 2012). United States, Arizona, Graham County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.56 - 09.3; 1,085 m (3,559 ft) elevation. This point southwest of Duncan, AZ currently consists of a dry playa at which there is no longer any evidence of a spring or *ciénaga*. **D**
 27. *Ciénaga Creek*. Hare, Trevor, pers. comm. (2014). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.0203 -110.4032; 977 m (3,206 ft) elevation. Located near Vail, AZ, *Ciénaga Creek* flows more than 48 km from near Sonoita to near Vail. Perhaps 16–24 km of the creek supports vast *ciénagas* along with cottonwood/willow gallery forests and mesquite bosques. Currently there are extensive *ciénegas* at the confluence of two main tributaries and a few smaller areas at the confluence of some of the drier tributaries. **F**
 28. *Ciénaga del Cuervo*. Sivinski, Robert, pers. comm. (2013). United States, New Mexico, Catron County. Aquatic ecoregion (river basin)—Gila. Coordinates: 33.23 -109.02; 1,485 m (4,871 ft) elevation. Located northeast of Morenci, just inside the NM border, there is no longer a *ciénaga* anywhere near this point, only a narrow canyon with a creek. *Ciénaga del Guiso* appears on the Military Map of New Mexico 1864 at 33.22 -108.98 and these two were likely one and the same. **D**
 29. *Ciénaga de Heradia*. Sivinski, Robert, pers. comm. (2013). Mexico, Sonora, Cananea municipio. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.13 -110.21; 1,422 m (4,666 ft) elevation. This *ciénaga* occurs south of Sierra Vista, AZ, 10.5 km south of the border. There is currently a dry swale at this location, but with small *ciénaga* remnants up-drainage, mostly behind dams. **S**
 30. *Ciénaga de los Pinos*. United States, Arizona, Pima County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.998207 -110.5930081; 1,065 m (3,495 ft) elevation. This *ciénaga* occurs 27.4 km (17 mi) west of Benson, near I-10. There appears to be a short spring run in an otherwise dry creek bed at this location. The adjacent valley floodplain is broad and may have once been a large *ciénaga*, but is now dry and covered in woody vegetation. **D**
 31. *Ciénaga del Macho* (also known as: *Ciénaga del Macho River*). Pearce. (1965). United States, New Mexico, County. The location and condition of this *ciénaga* remain unknown to the authors. **D**
 32. *Ciénaga La Palmita*. Minckley et al. (2012). Mexico, Sonora, Cananea municipio. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.2393 -110.2884; 1,442 m (4,730 ft) elevation. This location is south of Sierra Vista, 10.5 km below the border. It appears that there is no longer a *ciénaga* here. **D**
 33. *Ciénaga Mi Ranchito*. Minckley et al. (2012). Mexico, Sonora, Cananea municipio. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.065000 -110.31; 1,573 m (5,162 ft) elevation. Located north of Cananea, Sonora, there is no longer a *ciénaga* here. **D**
 34. *Ciénaga Molina* (also known as: *Rio San Rafael Ciénaga*). Minckley et al. (2012). Mexico, Sonora, Cananea municipio. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.161 -110.331; 1,422 m (4,666 ft) elevation. Southeast of Santa Cruz, AZ, and 19.3 km (11.4 mi) south of the border, this *ciénaga* currently has a dam built across it. **S**
 35. *Ciénaga Rio Magdalena*. Sivinski, Robert, pers. comm. (2014). Mexico, Sonora, Nogales municipio. Aquatic ecoregion (river basin)—Sonora. Coordinates: 31.095 -110.91; 1,101 m (3,613 ft) elevation. Located between Agua Zarca and Cibuta, below Nogales, Sonora, there is no longer water here, but instead a dry drainage and agricultural fields. **D**
 36. *Ciénaga Springs*. Sivinski, Robert, pers. comm. (2013). United States, New Mexico, Socorro County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 33.8731 -107.0894; 1,878 m (6,163 ft) elevation. Located 27.4 km (17 mi) southwest of Socorro. **R**
 37. *Ciénaga-Town*. Sivinski, Robert, pers. comm. (2014). United States, New Mexico, Hidalgo County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.695091 - 109.045125; 1,157 m (3,795 ft) elevation. This point in the Gila Valley between Virden and Duncan, AZ has long been converted to cropland. **D**
 38. *Ciénaga del Burro Creek* (also known as: *Cienequilla Creek*). Pearce (1965); Julyan (1996). United States, New Mexico, Union County. Aquatic ecoregion (river

- basin)—US Southern Plains. Coordinates: 36.59 -103.00; 1,449 m (4,753 ft) elevation. Julian (1996, 330–331) mentions both Seneca and Seneca Creek, 22.5 km northeast of Clayton, where the creek runs into Oklahoma. He notes that when freighters came through in the 1850s, they called it Jackass Swamp. This area is heavily farmed, with no suggestion of a live *ciénaga*. **D**
39. *Ciénega El Tule*. Minckley et al. (2012). Mexico, Sonora, Naco municipio. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.294 -110.28; 1,495 m (4,905 ft) elevation. Located south of Sierra Vista, AZ and 4 km across the border in Sonora, this *ciénaga* appears dead. Several large trees can be seen in Google Earth, but this site is otherwise covered with woody shrubs. **D**
40. *Ciénega Fresnal*. Jones, Dave, pers. comm. (2013). Mexico, Chihuahua. Aquatic ecoregion (river basin)—Guzman—Samalayuca. Coordinates: 31.04594 -107.530421; 1,181 m (3,875 ft) elevation. We learned of this *ciénaga* from our neighbor, Dave Jones, who lives in Casas Grandes, Chihuahua, but owns the Thorn Ranch south of our Pitchfork Ranch. He travels past this *ciénaga* regularly and informed us of its existence. We have not personally visited the property, but Google Earth imagery (viewed June 3, 2015) illustrates an approximately 7.4 km² (5 mi²) triangular-shaped area that appears to have springs and *ciénaga*-like and riparian vegetation. This is on the south edge of El Fresnal playa, just NW of the small community or rancho of El Fresnal. The area looks quite dry in the 2013 imagery in Google Earth, but images from 8/26/2007 and some earlier coverages indicate much greener vegetation. **F**
41. *Ciénega Springs*. Hendrickson and Minckley (1985). United States, Arizona, Graham County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.7204 -109.7046; 979 m (3,213 ft) elevation. Located south of Safford, AZ, the main spring for this *ciénaga* is now captured in an impoundment called Dankworth Pond. **S**
42. *Ciénega*—Unnamed. Mexico, Sonora, Cananea municipio. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.174 -110.33014; 1,402 m (4,600 ft) elevation. Located in Mexico between Sierra Vista, AZ and Cananea, Sonora, the area appears dry, with the adjacent dam full of sediment. **D**
43. *Ciénega Villa Verde*. Minckley et al. (2013). Mexico, Sonora, Cananea municipio. Aquatic ecoregion (river basin)—Sonora. Coordinates: 31.140000 -110.007000; 1,492 m (4,896 ft) elevation. Located northeast of Cananea and south of Naco, Sonora, this *ciénaga* occurs near a large dam impoundment and cropland. Further upstream is the town of El Suez, which appears to be built at a spring [31.17 -109.98] that no longer functions as a *ciénaga*. **S**
44. *Cieneguilla*. Bandelier et al. (1966). United States, New Mexico, Unknown County. Aquatic ecoregion (river basin)—unknown. “Little Marsh” or “Little Marshy Meadow.” This *ciénaga* has not been located by the authors and is likely dead. **D**
45. *Cienequita Las Cienagas*. Sartor, Karla, pers. comm. (2012). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.4745 -110.3546; 1,678 m (5,504 ft) elevation. Located approximately 72.4 km (45 mi) south of Tucson, this small *ciénaga* is fully functioning. **F**
46. *Cloverdale Ciénaga*. Sivinski and Tonne (2011). United States, New Mexico, Hidalgo County. Aquatic ecoregion (river basin)—Guzman—Samalayuca. Coordinates: 31.4367 -108.9764; 1,643 m (5,390 ft) elevation. Cloverdale Ciénaga is located west of Antelope Wells, in the Bootheel, NM, in the southwest corner of Hidalgo County. This large, discontinuous area of wet valley bottom contains a 20.2 ha remnant of a formerly large *ciénaga* with extensive plant diversity. This *ciénaga*, now damaged by excavation, down-cutting, and pasturing, is currently undergoing comprehensive restoration. **R**
47. *Cocospera Ciénega* (Rorabaugh and others (2013)). Mexico, Sonora, Imuris municipio. Aquatic ecoregion (river basin)—Sonora. Coordinates: 30.853826 -110.66469; 1,073 m (3,519 ft) elevation. Located west of Cananea, Sonora, there may remain a spring here, but this area is completely disturbed by agricultural fields, pastures, and farm ponds. Rorabaugh and others (2013) mention *ciénegas* on this ranch and state “federal reserve status for Rancho El Aribabi through México’s federal La Comisión Nacional de Áreas Naturales Protegidas (CONANP) . . . was assigned to the ranch in May of 2011.” See also <http://elaribabi.com/>. **R**
48. *Cold Spring Ciénaga*. Sivinski and Tonne (2011). United States, New Mexico, Grant County. Aquatic ecoregion (river basin)—Guzman—Samalayuca. Coordinates: 32.5636 -108.0094; 1,538 m (5,047 ft) elevation. Located southeast of Silver City, this *ciénaga* is completely dead, having been dewatered by Hurley copper mill. (Sivinski, Robert, pers. comm., 2014). **D**
49. *Comanche Springs Ciénaga*. Hendrickson, Dean A., pers. comm. (2014). United States, Texas, Pecos County. Aquatic ecoregion (river basin)—Pecos. Coordinates: 30.8815 -102.8787; 897 m (2,944 ft) elevation. Per Hendrickson, this *ciénaga* is in the middle of the city of Fort Stockton, long dry and functionally dead, although the city has a plan to restore it similar to what was done at Balmorhea. **S**
50. *Cook’s Lake*. Minckley et al. (2013). United States, Arizona, Pinal County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.862 -110.72; 648 m (2,127 ft) elevation. South of Dudleyville, near agriculture fields, this *ciénaga* appears dead. **D**
51. *Cook Spring*. Sivinski and Tonne (2011). United States, New Mexico, Socorro County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 34.0476 -106.9375; 1,493 m (4,899 ft) elevation. Located only 4 km west of Socorro, the status of this *ciénaga* is unclear, but a small amount of *ciénaga* habitat is apparent on aerial imagery and it is presumably restorable. **R**

52. Croton Springs. The source of this information is misplaced. United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.161 -109.93; 1,262 m (4,141 ft) elevation. Located at the edge of the Wilcox Playa, 13.7 southwest of Wilcox, this ciénaga is dead. **D**
53. Cow Springs. Sivinski, Robert, pers. comm. (2013). United States, New Mexico, Luna County. Aquatic ecoregion (river basin)—Guzman—Samalayuca. Coordinates: 32.4121 -108.1793; 1,537 m (5,042 ft) elevation. Located approximately 42 km south of Silver City, this ciénaga is on private property, captured and capped to prevent undermining the nearby ranch headquarters. "Early on, the spring or 'Ojo' was a deep well in the center of a plain, depressed somewhat below ground level. Several holes have been dug about 1.5 m (5 ft) around the natural spring to increase access to the water supply. The edge of the ojo is boggy and full of rushes. The water is good and slightly sulfurous, but full of vegetable matter and microscopic life. The evaporation of the surface water appears to keep pace with the bubbling up from the spring, since there is no stream emitted from it, a slightly marshy condition of the ground being the only effect" (Report for Explorations and Surveys [1857, 21]). The report notes Ojo de la Vaca's importance in the district where the supply of water is limited as but only one of three [water] sources immediately on the present wagon road. In the 1800s, this ciénaga was central to travelers to and from any of the four directions. **R**
54. Croton Springs. Hendrickson and Minckley (1985). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.17 -109.93; 1,264 m (4,147 ft) elevation. Located between Benson and Wilcox, 1.6 km south of I-10, there is no longer a spring or ciénaga at this location. **D**
55. Cuatro Ciénegas. Meyer (1973). Mexico, Coahuila de Zaragoza, Cuatro Ciénegas municipio. Aquatic ecoregion (river basin)—Rio Salado. Coordinates: 26.909135 -102.063279; 714 m (2,344 ft) elevation. This large ciénaga complex is located south of Big Bend, TX, and consists of thousands of acres of wetlands in a basin at the eastern edge of the Chihuahuan desert in the Mexican state of Coahuila. These are fed by abundant subterranean water that emerges at the surface in numerous small and large spring runs, seeps, and sink-hole ponds. No attempt is made here to catalog the spring, lake, and wetland names in this large artesian basin. The valley of Cuatro Ciénegas has the greatest number of endemic species of any place in North America and with its diverse complex of thousands of geothermal springs, marshes, lakes, and streams, it ranks near the Galápagos Islands in terms of the world's unique ecosystems (Meyer 1973). **F**
56. Dead Oryx Mound Spring. Sivinski and Tonne (2011). United States, New Mexico, Lincoln County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 33.417 -106.2864; 1,317 m (4,320 ft) elevation. This is a very small pool with little vegetation and barely alive. **S**
57. Diamond-Y Ciénaga. Hendrickson, Dean A., pers. comm. (2014). United States, Texas, Pecos County. Aquatic ecoregion (river basin)—Pecos. Coordinates: 31.02149 -102.90533; 838 m (2,748 ft) elevation. Located in Pecos County, the 1,603 ha Diamond Y Spring Preserve is now owned by The Nature Conservancy and provides the only remaining natural habitat for the federally listed Leon Springs pupfish (*Cyprinodon bovinus*) and the Pecos Gambusia (*Gambusia nobilis*). **F**
58. Douglas Valley Ciénaga. Hendrickson and Minckley (1985). Mexico, Sonora, Agua Prieta municipio. Aquatic ecoregion (river basin)—Sonora. Coordinates: 31.2243 -109.6; 1,261 m (4,137 ft) elevation. Occurring 6.4 km (4 mi) northwest of Douglas, AZ, this drainage is now dry. **D**
59. El Jarral Ciénaga. Meyer (1973). Mexico, Sonora, Cananea municipio. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.22 -110.34; 1,424 m (4,671 ft) elevation. Known to have existed in the late 1970s and located 37 km (23 mi) south of Sierra Vista, AZ, in Sonora, this location is a dry, broad drainage that no longer supports a ciénaga. **D** (Meyer 1973).
60. Empire Ranch (also known as: Ciénega Creek, Empire Ranch, and Ciénega Ranch (Minckley et al. 2013). USGS Topo Quad-Empire Mtn. 15-min series (1958). United States, Arizona, Pima County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.7879 -110.6400; 1,416 m (4,646 ft) elevation. The Empire Ranch is located approximately 35.4 km (22 mi) from Green Valley. Near the Empire Ranch Airport, on the west side of Ciénega Creek in Las Ciénegas National Conservation Area. There is extensive ciénaga habitat on this property (now BLM reserve). **F**
61. Fairbank Ciénaga. Hendrickson and Minckley (1985). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.717647 -110.196925; 1,178 m (3,850 ft) elevation. Located on the Babocomari River at its confluence with the San Pedro River, this site is now a mere valley bottom, and no longer supports a ciénaga. **D**
62. Faywood Ciénaga. Sivinski and Tonne (2011). United States, New Mexico, Grant County. Aquatic ecoregion (river basin)—Guzman—Samalayuca. Coordinates: 32.5613 -107.9875; 1,537 m (5,042 ft) elevation. Located some 37 km (23 mi) southeast of Silver City, this ciénaga is no longer functional. Although still wet, water is piped down from its original source up-canyon. **D**
63. Feldman-San Pedro Ciénaga. Hendrickson and Minckley (1985). United States, Arizona, Pinal County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.84 -110.71; 661 m (2,168 ft) elevation. Located between Dudleyville and Mammoth, 78.9 km (49 mi) northeast of Tucson, this is now only a valley bottom, and is no longer a ciénaga. **D**
64. Fort Grant Ciénaga. Hendrickson and Minckley (1985).

- United States, Arizona, Graham County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.58 -109.97; 1,380 m (4,526 ft) elevation. Located just 2.4 km (1.5 mi) from the Graham County seat, this site is no longer a *ciénaga*. **D**
65. Garden Canyon *Ciénega*. Minckley et al. (2012). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.454 -110.376; 1,896 m (6,222 ft) elevation. An on-site inspection is necessary to confirm the past occurrence of a *ciénaga* here, but this location, 13.57 km (8 mi) southwest of Sierra Vista, appears to no longer support a *ciénaga*. **D**
66. Greenwell Slough *Ciénega*. Minckley et al. (2012). United States, Arizona, Yavapai County. Aquatic ecoregion (river basin)—Gila. Coordinates: 34.716 -111.919; 604 m (1,983 ft) elevation. Located a mere 11.3 km (7 mi) north of the Scottsdale airport and just north of four large subdivisions, this site appears dry. **D**
67. Guilez Spring (also known as: Tula Pond). Sivinski and Tonne (2011). United States, New Mexico, Otero County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 33.0599 -106.1537; 1,263 m (4,143 ft) elevation. This site is an aridland spring with a 15.24 m (50 ft)-diameter pond that has been damaged by recreational use, exotic fish introduction, and road construction. Recent policy changes by the Department of Defense may well prohibit further damage. **R**
68. Harden *Ciénega* Creek. Minckley et al. (2013). United States, Arizona, Greenlee County. Aquatic ecoregion (river basin)—Gila. Coordinates: 33.197000 -109.125; 1,257 m (4,123 ft) elevation. Located 24.1 km (15 mi) northeast of Clifton in Greenlee County, the coordinates appear wrong, being too far to the east and up-slope of an extremely lush canyon. Although there is no evidence of a nearby *ciénaga*, because of the vegetation, location of multiple canyons, distance from development, nearness to another lush riparian canyon up-channel, and a well-established farming operation 3.2 km (2 mi) to the northwest, an on-site inspection of this isolated area may well identify wetlands. Although speculative, a tentative classification of restorable seems warranted. **R**
69. Hare Mound Spring. Sivinski and Tonne (2011). United States, New Mexico, Lincoln County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 33.409 -106.2932; 1,312 m (4,305 ft) elevation. This spring, a mere 25 cm in diameter (10 in), is the smallest of five in a cluster and is going naturally extinct (Sivinski, pers. comm., 2013). **D**
70. Heron Spring *Ciénega*. Minckley et al. (2013). United States, Arizona, Santa Cruz County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.352556 -110.576237; 1,430 m (4,693 ft) elevation. A small pond remains at this site, which no longer supports a *ciénaga* or riparian vegetation. This site is damaged by livestock. **S**
71. Hooker *Ciénega*. Hendrickson and Minckley (1985). United States, Arizona, Graham County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.51 -110.04; 1,338 m (4,389 ft) elevation. Located some 48.3 km (30 mi) southwest of Safford, this *ciénaga* is dead. **D**
72. Horseshoe Canyon *Ciénega*. Sivinski, Robert, pers. comm. (2013). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.76 -109.06; 1,298 m (4,258 ft) elevation. Located near the AZ/NM border, 69.2 km (43 mi) northeast of Douglas, this *ciénaga* is completely dry. **D**
73. Howard *Ciénega*. Google Maps Satellite View (2013). United States, New Mexico, Grant County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.9801 -108.6564; 1,432 m (4,699 ft) elevation. Surrounded by buildings on a farm, this *ciénaga* appears dead on Google Earth, likely from pumping (Sivinski, pers. comm., 2014). **D**
74. Hulsey *Ciénega*. Google Maps Satellite View (2013). United States, New Mexico, Catron County. Aquatic ecoregion (river basin)—Gila. Coordinates: 33.863700 -108.9019; 2,121 m (6,959 ft) elevation. This location is under 8 km northeast of Luna, in an unincorporated village in northwest Catron County, NM, 11.3 km (7 mi) from the NM/AZ border, 33.8 km (21 mi) from Reserve on the San Francisco River, and east of the road to Bastion Ranch. On Google Earth, there appears to be a string of 18 wet spots, a good deal of water, agriculture and impoundments; although unclear, this is likely a functional *ciénaga*. **F**
75. Indian Hot Spring (also known as: Eden Hot Springs). Minckley et al. (2013). United States, Arizona, Graham County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.9988 -109.9025; 849 m (2,785 ft) elevation. Located near Fort Thomas, 25.8 km (16 mi) northwest of Safford, this spring is highly disturbed and overrun by salt cedar, but may be salvageable. **S**
76. Jaques Marsh. Sivinski, Robert, pers. comm. (2013). United States, Arizona, Navajo County. Aquatic ecoregion (river basin)—Colorado. Coordinates: 34.1889 -109.9826; 2,067 m (6,782 ft) elevation. Just under 8 km (5 mi) north of Pinetop-Lakeside, this location appears to be obliterated by an agricultural field (Sivinski, pers. comm., 2013). **D**
77. Kennecott Cold Spring. Sivinski, Robert, pers. comm. (2013). United States, New Mexico, Grant County. Aquatic ecoregion (river basin)—Guzman—Samalayuca. Coordinates: 32.5647 -108.0078; 1,539 m (5,050 ft) elevation. As with the other three desert springs and *ciénagas* clustered at the dry mouth of the Rio Mimbres, this one also has been dried up by wells dug to supply water to the copper mill at Hurley (Sivinski, pers. comm., 2013). **D**
78. Kennecott Warm Spring. Sivinski, Robert, pers. comm. (2013). United States, New Mexico, Grant County. Aquatic ecoregion (river basin)—Guzman—Samalayuca. Coordinates: 32.5633 -108.0078; 1,536 m (5,040 ft) elevation. This *ciénaga* is completely dead, drained in

- service of the Hurley copper mill (Sivinski, pers. comm, 2014). **D**
79. Kewa Marsh. Sivinski and Tonne (2011). United States, New Mexico, Sandoval County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 35.5459 -106.3516; 1,691 m (5,548 ft) elevation. Located 40.2 km (25 mi) west of Santa Fe and 8 km north of Santo Domingo Pueblo, this is a significant, extensive 2.6 km (1.6 mi)-long, 202 ha (500 ac), functional ciénaga. **F**
 80. La Cebadilla Springs. Source unknown. United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.144 -110.4118; 1,453 m (4,766 ft) elevation. Located 22.5 km (14 mi) north and slightly west of Benson, AZ, this little-known ciénaga has live water and is functioning as well as most of the few ciénagas that remain. It would benefit from restoration. This coordinate indicates a spot on dry hills that has neither a spring nor a ciénaga, although there is an area about a mile to the northeast (32.1571 - 110.4054) with a grassy bottom and a few trees. The location and identical name to ciénaga #81, require further inquiry. **F**
 81. La Cebadilla Spring. Minckley et al. (2013). United States, Arizona, Pima County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.2448 -110.6881; 830 m (2,724 ft) elevation. Located 24.1 km (15 mi) east of downtown Tucson, 4.8 km (3mi) east of the census-designated place of Tanque Verde and among well-spaced, large homes on multiple-acre lots, many with swimming pools, this area has two spring-fed ponds where ciénaga habitat has been excavated (destroyed) to make the ponds. Restoration is clearly called for. **R**
 82. La Cienaga de San Vicente. Martinez, D. H. (1785), cited in Alford (1982). United States, New Mexico, Grant County. Aquatic ecoregion (river basin)—Guzman—Samalayuca. Coordinates: 32.77 -108.28; 1,808 m (5,932 ft) elevation. Formerly occupying the site that is now Silver City, there were dozens of springs that fed the periphery of the extensive meadowlands of the Silver City floodplain at the confluence of the Silva and Piños Altos Creeks, a location frequented by the Apache. Floods in 1895 and 1902 transformed the street into the 54 ft-deep “Big Ditch” that now cuts through the town in lieu of Main Street (Alford, 1982). **D**
 83. La Fresna Ciénega (also known as: Los Fresnos, Rancho Los Fresnos). Esquer, Antonio and T. Hare, pers. comm. (2013); Rorabaugh et al. (2013). Mexico, Sonora, Santa Cruz municipio. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.28276736 -110.390000; 1,501 m (4,925 ft) elevation. The coordinates are of the El Fresno ranch headquarters. There is a small spring seep visible in Google Earth imagery dated 4/2013 up-drainage 4–5 km (3 mi) to the northwest (at 31.314118 - 110.426764) in the area apparently referred to by Rorabaugh et al. (2013) as having “well-developed ciénegas and riparian corridors along Portrero del Alamos, Arroyo Los Fresnos, Arroyo Los Alisos, Agua Dulce, and other drainages (Varela-Romero et al. 1992).” See also <http://www.naturalia.org.mx> **R**
 84. Lake Valley Ciénega. Sivinski and Tonne (2011). United States, New Mexico, Sierra County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 32.7581 -107.5353; 1,551 m (5,090 ft) elevation. This site at one time consisted of intermittent runoff from Berrenda Creek which was captured in Lake Valley sediments and slowly discharged into a perennial spring run at the base of Lake Valley to create ciénaga wetlands. Lake Valley Cienaga is now deeply incised; the ciénaga is gone and riparian woodlands remain. **D**
 85. Lang Ciénega (also known as: Ciénega Spring). Sivinski, Robert, pers. comm. (2013). United States, New Mexico, Hidalgo County. Aquatic ecoregion (river basin)—Guzman—Samalayuca. Coordinates: 31.335098 -108.816266; 1,572 m (5,158 ft) elevation. Located 25.8 km (16 mi) west of Antelope Wells, NM, approximately 90% of the ciénega lies in US and 10% in Mexico, covering 24.3 ha (60 ac) and 4 km (2.5 mi) long, this important ciénaga has high plant diversity and no problem with invasive plants. **F**
 86. Las Ciénagas. Hare, Trevor, pers. comm. (2014). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.0203 -110.4032; 977 m (3,206 ft) elevation. Located near Vail, AZ, the condition of this ciénaga is similar to Ciénega Creek, number 27 above. **R**
 87. Leslie Creek Ciénega. Hendrickson and Minckley (1985). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Yaqui. Coordinates: 31.591755 -109.488391; 1,433 m (4,701 ft) elevation. Located 30.6 km (19 mi) north of Douglas, this location is on the 1,119 ha (2,765 ac) Leslie Canyon National Wildlife Refuge established in 1988 to protect two of the eight native fish species of the Rio Yaqui watershed, the Yaqui chub (*Gila purpurea*) and the Yaqui topminnow (*Poeciliopsis occidentalis sonoriensis*). Wildlife Refuge Specialist Chris Lohrengrel (pers. comm., May 20, 2015) considers the location for which we provide coordinates to be most likely, based on current vegetation and soils, to have had a ciénaga. **R**
 88. Lewis Springs-San Pedro (also known as: Lewis Springs Ciénega and Bull Run). Hendrickson and Minckley (1985). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.578500 -110.1398; 1,234 m (4,050 ft) elevation. Located 27.4 km northeast of Sierra Vista, AZ, and some 400 m (1,312 ft) east of the San Pedro River near Saint David Cienaga, this ciénaga is slightly less than 0.8 ha (1 ac) in area and is one of the few known locations of the obligate wetland species cardinal flower (*Lobelia cardinalis*). It is also the location for the critically imperiled [in Arizona] Arizona eryngo (*Eryngium sparganophyllum*). **F**
 89. Los Ojos (also known as: Ojos de Agua Caliente). Minckley et al. (2013). Mexico, Sonora, Agua Prieta municipio. Aquatic ecoregion (river basin)—Guzman—

- Samalayuca. Coordinates: 31.2827 -108.9915; 1,753 m (5,750 ft) elevation. Located less than 4.8 km (3 mi) below the international border and 53 km (33 mi) east of Douglas, AZ, this appears to be a living ciénaga. **F**
90. Main Mound Spring. Sivinski and Tonne (2011). United States, New Mexico, Lincoln County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 33.4257 -106.2848; 1,325 m (4,347 ft) elevation. The largest of five clustered springs 186.7 km (116 mi) south of Albuquerque, in the northern part of the White Sands Desert, this ciénaga provides habitat for the White Sands pupfish (*Cyprinodon tularosa*) and healthy ciénaga vegetation. **F**
91. Malpais Spring Ciénega. U.S. Dept. of Defense. Sivinski and Tonne (2011). United States, New Mexico, Otero County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 33.2786 -106.3101; 1,262 m (4,140 ft) elevation. Located in the north portion of the White Sands Desert and 53.1 km (33 mi) northwest of Alamogordo, both the size and healthy condition of this reclaimed ciénaga are rare. This ciénaga provides habitat for the White Sands pupfish (*Cyprinodon tularosa*). **F**
92. Martin Ciénega. Hough, W. (1907). United States, New Mexico, Catron County. Aquatic ecoregion (river basin)—Gila. Coordinates: 33.8189 -108.9545; 2,150 m (7,055 ft) elevation. This location is in Luna, covered by a road and next to the asphalt parking lot for the USDA Forest Service Apache National Forest. **D**
93. Mescal Warm Spring. Hare, Trevor, pers. comm. (2014). United States, Arizona, Pinal County. Aquatic ecoregion (river basin)—Gila. Coordinates: 33.148458 -110.635187; 760 m (2,494 ft) elevation. Located in the Needles Eyes Wilderness area in the Mescal Mountains, this ciénaga is spring-fed on a mesa above Mescal Creek with a hanging garden below along the creek. **F**
94. Monkey Spring. Minckley et al. (2013). United States, Arizona, Santa Cruz County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.639 -110.711; 1,387 m (4,550 ft) elevation. Located less than 9 km (5.6 mi) southwest of Sonoita, there is no ciénaga at this point, but there does appear to be a small spring pool and acequia to the southeast at 31.63 -110.70 elev. 1,415 m. **R**
95. Mule Spring. Hayes, Frank pers. comm. (2014). United States, New Mexico, Grant County. Aquatic ecoregion (river basin)—Gila. Coordinates: 33.09859 -108.981535; 1,635 m (5,365 ft) elevation. Located near a long-occupied pre- and post-Classic Mimbres cultural site with a long history of occupancy, many ciénaga plants represented. **S**
96. Munson's Ciénega (also known as: San Simon-Gila). United States, Arizona, Graham County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.826 -109.627; 904 m (2,965 ft) elevation. Located 8 km east of Safford, and 1.6 km (1 mi) north of Solomon, AZ, this site is now merely a floodplain that has been completely converted to cropland. (Sivinski, pers. comm., 2014). **D**
97. North Mound Spring. Sivinski and Tonne (2011). United States, New Mexico, Lincoln County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 33.4353 -106.2896; 1,330 m (4,365 ft) elevation. Part of a cluster of springs, North Mound Spring is only 76 cm (30 in) across, consisting of a gypsum mound spring with little vegetation. **S**
98. Oak Tree Ciénega. Hare, Trevor, pers. comm. (2014). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.0203 -110.4000; 977 m (3,206 ft) elevation. This ciénaga exists along Ciénega Creek at its confluence with Oak Tree Canyon. **F**
99. Obed Meadow Ciénega. Google Maps Satellite View (2013). United States, Arizona, Navajo County. Aquatic ecoregion (river basin)—Colorado. Coordinates: 34.917 -110.390; 1,527 m (5,009 ft) elevation. Located 128.7 km (80 mi) east of Flagstaff and just over 3.2 km (2 mi) south of Joseph City, on Google Earth Obed Meadow appears undisturbed, but with no ciénaga. **D**
100. Ojo de Agua. Minckley et al. (2013). Mexico, Sonora, Cananea municipio. Aquatic ecoregion (river basin)—Sonora. Coordinates: 30.96 -110.232; 1,486 m (4,874 ft) elevation. Located east of Cananea and 40.2 km (25 mi) south of the border, this former ciénaga has been replaced by a salt flat reservoir. **D**
101. Ojos de Arrey (also known as: Ojo del Rey). Sivinski, Robert, pers. comm. (2013). Mexico, Chihuahua, Galeana municipio. Aquatic ecoregion (river basin)—Guzman—Samalayuca. Coordinates: 30.05948 -107.590129; 1,498 m (4,915 ft) elevation. Located 5.8 km (3.6 mi) southeast of Galeana, this appears to be a large spring ciénaga on aerial imagery. **F**
102. Ojo de Huelos (also known as: Ojo Alamo). Sivinski, Robert, pers. comm. (2013). United States, New Mexico, Valencia County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 34.7317 -106.5461; 1,650 m (5,414 ft) elevation. Valencia Co. Located 19.3 km (12 mi) southeast of Los Lunas, this ciénaga is currently almost completely dry and probably not restorable. **D**
103. Ojito de San Juan. Torres, Frank, pers. comm. (2014). United States, New Mexico, Grant County. Aquatic ecoregion (river basin)—Guzman—Samalayuca. Coordinates: 32.89 -107.84; 2,152 m (7,060 ft) elevation. Coordinates estimated (believed within several km). Previously unknown to anyone, this small ciénaga is located 8 km (5 mi) north of San Juan Church near the Mimbres River. Ojito de San Juan is currently unfenced and services a 1.9 m³ (67 ft³) drinker for cattle. It is referred to locally as an *ojito* or "little spring." Torres states that this site is used to water cattle and is surrounded by black soil and what he describes as ciénaga-like vegetation. A site visit is planned, and it seems probable this small ciénaga would benefit from fencing, a drinker, and restoration at little cost; this would also be of benefit for watering cattle. **R**

104. Ojo Vareleno. Sivinski, Robert, pers. comm. (2013). Mexico, Chihuahua, Casas Grandes municipio. Aquatic ecoregion (river basin)—Guzman—Samalayuca. Coordinates: 30.4006 -107.9847; 1,529 m (5,018 ft) elevation. Located 104.6 km (65 mi) south of the international border and 4 km (2.5 mi) northwest of Casas Grandes, Ojo Vareleno is partially developed but currently represents a good living ciénaga. **R**
105. Palomas Canyon Ciénega. Sivinski and Tonne (2011). United States, New Mexico, Sierra County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 33.1713 -107.5601; 1,643 m (5,392 ft) elevation. Located 82 km (51 mi) northeast of Silver City, Palomas Canyon Cienaga is a little-known seep cienaga (300 m x 30 m, 984 ft x 98 ft) that is largely intact. **F**
106. Parker Canyon Ciénega. Minckley et al. (2013). United States, Arizona, Santa Cruz County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.421 -110.467; 1,603 m (5,259 ft) elevation. Located 22.5 km southwest of Sierra Vista and less than 1.6 km (1 mi) west of Parker Canyon Lake, this location is in a canyon with vegetation, but no ciénaga is apparent. Although inspection is needed to confirm, this ciénaga appears dead. **D**
107. Potrero Canyon Ciénega. Minckley et al. (2013). United States, Arizona, Santa Cruz County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.39 -110.957; 1,113 m (3,653 ft) elevation. This location is 8 km (5 mi) south of Rio Rico, midway toward Nogales. From Google Earth, there no longer appears to be a ciénaga at this site, although inspection is needed to confirm. **D**
108. Pipe Springs Ciénega. Makings (2013). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Yaqui. Coordinates: 31.33528 -109.260516; 1,135 m (3,724 ft) elevation. This ciénaga is mentioned in Makings (2013) and is on a refuge managed by the staff of the San Bernardino National Wildlife Refuge in Cochise County, AZ. Bill Radke, manager of the Refuge (pers. comm., 2014) states that there are several capped steel pipes in this area that flowed freely in the past and may have supported ciénaga habitats. Dean Hendrickson collected fishes, Yaqui chub (*Gila purpurea*) and Yaqui topminnow (*Poeciliopsis occidentalis sonoriensis*), at Pipe Springs Ciénega (he recalls an old well casing) around 1979–80 (pers. comm., 2015). Chris Lohrengel, Wildlife Refuge Specialist at San Bernardino/Leslie Canyon National Wildlife Refuge (pers. comm., 2015) reports that the area would lend itself to a ciénaga and that there is an impoundment downstream that is ciénaga habitat with ciénaga-obligate plants associated with it. Due to location and other considerations, restoration is likely. **R**
109. Quetes de la Ciénaga. Bandelier et al. (1966). United States, New Mexico, unknown County. Aquatic ecoregion (river basin)—unknown. Presumably NM. We misplaced the specific page, but initially found this ciénaga mentioned in Bandelier's 1892 reports (Bandelier et al. 1966). The location and condition of this ciénaga is unknown, but it is presumed dead. **D**
110. Redhead Marsh. Google Maps Satellite View (2013). United States, Arizona, Navajo County. Aquatic ecoregion (river basin)—Colorado. Coordinates: 34.29504 -110.07483; 1,914 m (6,280 ft) elevation. Redhead Marsh is located 6.4 km (4 mi) north of Show Low. There is nearby water and what appears to be a large built impoundment 2.6 km (1.6 mi) southeast of Redhead Marsh. It is possible, but doubtful that a ciénaga occurs here. **D**
111. Redington-San Pedro Ciénaga. Hendrickson and Minckley (1985). United States, Arizona, Pima County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.43 -110.50; 886 m (2,908 ft) elevation. Located 22.5 km southeast of San Manuel, this ciénaga no longer exists. **D**
112. Oasis Dairy Ciénaga. Sivinski and Tonne (2011). United States, New Mexico, Chaves County. Aquatic ecoregion (river basin)—Pecos. Coordinates: 33.31449 -104.3712; 1,390 m (4,560 ft) elevation. This unnamed spring and associated large ciénaga is a part of the Roswell Artesian Basin Ciénegas, 11.3 km (7 mi) east of Roswell, Chaves County, NM, opposite Bottomless Lakes State Park. The ciénaga is rapidly declining due to agricultural pumping and appears to be dying (Sivinski, pers. comm., 2014). **S**
113. Phantom Lake Spring (also known as: Phantom Springs Cave and Ojo la Loma on an early map). Hendrickson, Dean A., pers. comm. (2014). United States, Texas, Jeff Davis County. Aquatic ecoregion (river basin)—Pecos. Coordinates: 30.9348 -103.8486; 1,060 m (3,478 ft) elevation. This is actually a group of springs that pour from a 141 m (88 ft)-deep cave at the foot of the lower Cretaceous limestone bluff 6.4 km (4 mi) west of Toyahvale. It is the deepest underwater cave system known in the United States. The cave feeds the 6.4 km (4 mi)-long Phantom Lake Canal built in the 1940s that carries water for irrigation, although irrigation wells have caused the spring flow to decline from 450^{l/s} in 1932 to 140^{l/s} in 1976. The cave is the home of two federally and Texas-listed endangered fish: Comanche Springs pupfish (*Cyprinodon elegans*) and Pecos gambusia (*Gambusia nobilis*). <https://tshaonline.org/handbook/online/articles/rpp06>. **F**
114. Dexter Ciénega. Sivinski and Tonne (2011). United States, New Mexico, Chaves County. Aquatic ecoregion (river basin)—Pecos. Coordinates: 33.2407 -104.37015; 1,052 m (3,452 ft) elevation. Located adjacent to the Dexter National Fish Hatchery, this ciénaga is severely impacted by roads, dikes, impoundments, and changed hydrology from hatchery operations. **S**
115. BLM Overflow Wetland. Sivinski, Robert, pers. comm. (2013). United States, New Mexico, Chaves County. Aquatic ecoregion (river basin)—Pecos. Coordinates: 33.3089 -104.3443; 1,050 m (3,444 ft) elevation. This wetland consists of a large salt marsh and ciénaga created in a valley bottom flooded by spring flow from

- adjacent sinkhole lakes that overlap part of Bottomless Lakes State Park. **F**
116. BLM North Dexter Ciénaga. Sivinski and Tonne (2011). United States, New Mexico, Chaves County. Aquatic ecoregion (river basin)—Pecos. Coordinates: 33.26915 -104.36353; 1,047 m (3,434 ft) elevation. Located 8 km north of Dexter, a spring at the head of a valley created a ciénaga over 1.6 km (1 mi) long. This was dried by a well, but after purchase by BLM, this ciénaga is slowly recovering. **R**
 117. Rio Rico Ciénaga. Minckley et al. (2012). United States, Arizona, Santa Cruz County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.478 -110.988; 1,038 m (3,405 ft) elevation. Located 2.4 km north of Rio Rico, this site appears to be on the edge of an abandoned agricultural field. This former ciénaga is dead. **D**
 118. Saint David-San Pedro Ciénaga (also known as: Tenneco Marsh and Miller's Marsh). Hendrickson and Minckley (1985). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.8422 -110.2235; 1,260 m (4,134 ft) elevation. Located 6.4 km south of St. David, AZ, just west of the San Pedro River, this is a large ciénaga (approximately 141.6 ha) with a 4 km perimeter that contains approximately 30.4 ha of permanent water. This is a well-preserved, recovering ciénaga, managed by the BLM as part of the San Pedro Riparian National Conservation Area. **F**
 119. Saracachi Ciénaga. Hare, Trevor, pers. comm. (2014). Mexico, Sonora, Cucurpe municipio. Aquatic ecoregion (river basin)—Sonora. Coordinates: 30.3591 -110.5986; 941 m (3,087 ft) elevation. Located less than 3.2 km west of Agua Fria, and 103 km south of the AZ border, this is a large ciénaga, greater than 81 ha and in excellent condition. **F**
 120. San Bernardino Ciénaga (also known as: San Bernardino Ranch and Slaughter Ranch). Minckley and Brunelle (2007). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Yaqui. Coordinates: 31.337369 -109.261762; 1,136 m (3,727 ft) elevation. This former cienaga is 27.4 km east of Douglas on the U.S. side of the border. This ciénaga was dried by severe erosion and channel incision that lowered the water table and dried up the wetland. The only wet, living part of this ciénaga, artificially maintained by an artesian well, is on the Sonoran side of the border. **D**
 121. San Pedro-Complex. Hendrickson and Minckley (1985). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.47 -110.11; 1,291 m (4,234 ft) elevation. Equidistant between Sierra Vista and Bisbee, and less than 4.8 km north of Herford, this is a very complicated riparian system, very little of which can currently be called a ciénaga, but it is likely restorable. **R**
 122. San Simon Ciénaga (also known as: Cienaga de Sauz). Hendrickson and Minckley (1985). United States, New Mexico, Hidalgo County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.0746 -109.0481; 1,177 m (3,860 ft) elevation. Located on the NM/AZ border, 22 km (15.5 mi) north of Rodeo, NM. This was one of the most extensive ciénagas in the Southwest, being 8 km (5 mi) in length and up to 400 m (1312ft) wide. It has been completely dried by groundwater pumping in agricultural fields at the foot of the Chiricahua Mountains (Sivinski and Tonne 2011). The valley around this point is dry and there is no longer any chance of a ciénaga occurring here, despite expensive, now abandoned, government efforts. **D**
 123. Santa Cruz River Ciénaga. Minckley et al. (2013). United States, Arizona, Santa Cruz County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.36 -110.59; 1,446 m (4,743 ft) elevation. Located 33.8 km (21 mi) northeast of Nogales, Sonora and 4.8 km north of Santa Cruz, but in the US, a small ciénaga remains northeast of this point at 31.37 - 110.58. **R**
 124. City of Santa Rosa Ciénagas. Sivinski and Tonne (2011). United States, New Mexico, Guadalupe County. Aquatic ecoregion (river basin)—Pecos. Coordinates: 34.9426 -104.6762; 1,412 m (4,634 ft) elevation. There are 11 separate springs clustered in this basin. In order to maintain consistency with other ciénegas listed that also consist of multiple features, the many springs are treated as one. **F**
 125. Seco Canyon Ciénaga. Sivinski and Tonne (2011). United States, New Mexico, Sierra County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 33.0899 -107.5582; 1,682 m (5,518 ft) elevation. This ciénaga is located approximately 27.4 km (15 mi) west of Truth or Consequences, NM. This is an undisturbed, 80.5 m (264 ft)-long spring seep ciénaga. **F**
 126. Sharp Spring. Minckley et al. (2013). United States, Arizona, Santa Cruz County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.358 -110.581; 1,426 m (4,679 ft) elevation. Located 25.7 km (16 mi) southeast of Patagonia and less than 3.2 km (2 mi) from the international border, this site is near what appear on Google Earth to be abandoned agricultural fields and no ciénaga. **D**
 127. Sheehan property Ciénaga. Sivinski, Robert, pers. comm. (2013). United States, New Mexico, Guadalupe County. Aquatic ecoregion (river basin)—Pecos. Coordinates: 34.9197 -104.6723; 1,458 m (4,785 ft) elevation. This site contains a large spring and spring run within 2.4 ha (5.9 ac) of healthy cienaga. **F**
 128. Sheehy Spring. Minckley et al. (2013). United States, Arizona, Santa Cruz County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.373 -110.569; 1,467 m (4,813 ft) elevation. Located 25.7 (16 mi) km southeast of Patagonia and almost 4.8 km (3 mi) from the international border, this wetland is similar to Sharp Spring; there is no longer a ciénaga at this location. **D**
 129. Shorthorn Spring. Sivinski, Robert, pers. comm. (2013). United States, New Mexico, Sierra County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 32.7578 -107.3968; 1,366 m (4,483 ft)

- elevation. Located 25.7 km (16 mi) northeast of Hatch, this spring seep is captured for a cattle drinker, although overflow wets a 30 x 10 m (98 ft x 32 ft) grassy area. **R**
130. Sink Hole Ciénaga. Sivinski and Tonne (2011). United States, New Mexico, Chaves County. Aquatic ecoregion (river basin)—Pecos. Coordinates: 33.2789 -104.3502; 1,050 m (3,445 ft) elevation. This small habitat was created in the mid-1990s when the site was opened into a small ciénaga. **F**
 131. Sonoita Ciénaga. Minckley and Brunelle (2007). United States, Arizona, Santa Cruz County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.53 -110.77; 1,222 m (4,010 ft) elevation. Located 1.6 km (1 mi) southwest of Patagonia, AZ, it appears that the entire ciénaga has been converted to a hay meadow (Sivinski, pers. comm., 2013). **D**
 132. Sonora Ciénaga. Sivinski, Robert, pers. comm. (2013). Mexico, Sonora, Fronteras municipio. Aquatic ecoregion (river basin)—Sonora. Coordinates: 30.758468 -109.602612; 1,190 m (3,904 ft) elevation. Located less than 4.8 km (3 mi) northeast of Esqueda, Sonora, there is a remnant of a disturbed ciénaga upstream of an impoundment with associated hay fields and cropland. **R**
 133. South Mound Spring. Sivinski and Tonne (2011). United States, New Mexico, Lincoln County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 33.406 -106.2946; 1,309 m (4,295 ft) elevation. The second largest of five springs, South Mound Spring is sparsely vegetated and fenced from feral horses. **S**
 134. Stevens Ciénaga. Hough (1907). United States, Arizona, Navajo County. Aquatic ecoregion (river basin)—Colorado. Coordinates: 34.1296 -109.8962; 2,193 m (7,196 ft) elevation. This ciénaga is identified from a century-old archaeology paper. There no longer appears to be a ciénaga in this area 3.5 km (2.1 mi) east of Pinetop, AZ. While it is arguably too high in the mountains to be listed here, W. Hough's sketch indicates a large body of water in a valley-like setting that at one time supported a sizable number of people in a large open space. **D**
 135. Sulphur Springs. Hendrickson and Minckley (1985). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.09 -109.80; 1,274 m (4,180 ft) elevation. Located 14.5 km (9 mi) south of Wilcox, on the edge of the large Faria Dairy and numerous large agricultural fields, there may still be a spring at this location, but no ciénaga currently exists here. This habitat is unlikely to be restored due to groundwater pumping. **D**
 136. Sycamore Ciénaga. Minckley and Brunelle (2007). United States, Arizona, Maricopa County. Aquatic ecoregion (river basin)—Gila. Coordinates: 33.66 -111.66; 453 m (1,486 ft) elevation. Located northeast of Fountain Hills, this area is currently completely dry. **D**
 137. Tavaschi Marsh (also known as: Tavasel Marsh). Google Maps Satellite View (2013); Minckley et al. (2013). United States, Arizona, Yavapai County. Aquatic ecoregion (river basin)—Gila. Coordinates: 34.7781 -112.0221; 1,023 m (3,357 ft) elevation. Just over 3 km east of Clarkdale, there is a large marsh in what appears to be an old oxbow on the Verde River less than 100 m (328 ft) west at 34.77 - 112.02. **F**
 138. The Ciénaga. Google Maps Satellite View (2013). United States, Arizona, Apache County. Aquatic ecoregion (river basin)—Colorado. Coordinates: 34.27851 -109.394614; 1,904 m (6,248 ft) elevation. This site is located approximately 2.4 km (1.5) west of Hwy 180 between St. Johns and Eagar. **F**
 139. The Narrows-San Pedro Ciénaga. Hendrickson and Minckley (1985). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.11 -110.30; 1,034 m (3,391 ft) elevation. Located 16 km (10 mi) north and less than 0.5 km (0.3 mi) east of the San Pedro River, this area is completely dry and no ciénaga remains here. **D**
 140. Tres Alamos Wash Ciénegas. Minckley et al. (2013). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.037 -110.311; 1,050 m (3,446 ft) elevation. Located 8 km (5 mi) north of Benson, just east of the San Pedro River, this area is now completely dry. **D**
 141. Turkey Creek Ciénaga. Hendrickson and Minckley (1985). United States, Arizona, Santa Cruz County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.5395 -110.5128; 1,526 m (5,006 ft) elevation. This site occurs very close to Canelo Hills, and is likely dead. **D**
 142. Unnamed Ciénaga #1. Hendrickson and Minckley (1985). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.68 -109.13; 1,336 m (4,382 ft) elevation. Located 54.7 km (34 mi) northeast of Douglas, there is currently no ciénaga at this location. **D**
 143. Unnamed Ciénaga #2. Mapa Oficial del Estado Sonora Republica de Mexico (1924). Mexico, Sonora, Cananea municipio. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.21 -110.31; 1,413 m (4,636 ft) elevation. Located south of Sierra Vista, across the border, this was apparently a huge ciénaga in the past, but is now only a remnant. **S**
 144. Unnamed Ciénaga #3. Mapa Oficial del Estado Sonora Republica de Mexico (1924). Mexico, Sonora, Naco municipio. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.15 -110.05; 1,476 m (4,841 ft) elevation. Located southeast of Sierra Vista, AZ, 20.9 km south of the border, this spring-fed creek currently possesses a riparian woodland, but no ciénaga. **D**
 145. Unnamed Ciénaga #4. Sivinski, Robert, pers. comm. (2013). United States, Arizona, Graham County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.726 -109.7028; 974 m (3,196 ft) elevation. This is a wet, living ciénaga 2.6 km to the northwest of the Artesia ciénaga. **F**

146. Unnamed Ciénaga #5. Anonymous, pers. comm. (2013). United States, New Mexico, unknown County. Aquatic ecoregion (river basin)—unknown. Located near Mule Creek, upstream and to the east of an archaeological site, there is currently a pond and small marshy area here supported by manmade constructions with abundant water and marshy vegetation. **R**
147. Unnamed Ciénaga #6. Anonymous, pers. comm. (2013). United States, New Mexico, unknown County. Aquatic ecoregion (river basin)—unknown. This is near another archaeological site, likely restorable. **R**
148. Unnamed Ciénaga #7. Anonymous, pers. comm. (2012). United States, New Mexico, unknown County. Aquatic ecoregion (river basin)—unknown. We were informed of this functioning ciénaga at an Audubon meeting in Deming, NM, but the person worried that the property owners would not authorize disclosure. When he failed to follow up, the authors presumed the owners declined to give permission. **F**
149. Unnamed Ciénaga #8. Anonymous, pers. comm. (2013). United States, New Mexico, unknown County. Aquatic ecoregion (river basin)—unknown. Coordinates: m (ft) elevation. The authors were informed of this functioning ciénaga at an Audubon meeting in Deming, NM, in 2013. The person who informed us of the ciénaga's existence worried that the property owners would not authorize disclosure. The informant failed to follow up and we presume the owners declined to give permission. **F**
150. Unnamed Ciénaga #9. Varner, Nick, pers. comm. (2014). United States, New Mexico, Grant County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.8823 -108.2276; 2,046 m (6,712 ft) elevation. Located 12.9 km (8 mi) north of Silver City, this is a 3.7 m (12 ft)-diameter, spring-fed pool of water atop a 107 m (351 ft)-deep cave with a side drift that is said to go south at least 30 m (98 ft). Located on a 0.8 ha (1.9 ac) private residential property next to an old mine shaft just north of Pinos Altos, it is fenced in a manner to allow wildlife access. We believe this ciénaga has never before been included in published ciénaga lists. The landowners are interested in its importance and preservation. This ciénaga surely was named, but that information is lost and now the ciénaga could very well bear the name Bear Creek Ciénaga because a creek by that name is nearby, or Varner Ciénaga, bearing the name of the current owners. **F**
151. Water of the Dead-Klondike Ciénaga. Hendrickson and Minckley (1985). United States, Arizona, Graham County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.80 -110.28; 1,127 m (3,698 ft) elevation. Located 40.2 km (25 mi) northeast of San Manuel, this location is a dry wash and farm fields, and no longer a ciénaga. **D**
152. Whitewater Draw Ciénaga Minckley et al. (2013). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Guzman—Samalayuca. Coordinates: 31.468 -109.702; 1,223 m (4,012 ft) elevation. This location is 20.9 km (13 mi) northwest of Douglas and 43.5 km (27 mi) west of Adobe Double Elementary School near White Water Draw, a watercourse with the appearance on Google Earth of vegetation. Although there is no ciénaga at this location, due to its 483 m distance from the draw, and nearby features that seem to be watered on Google Earth, this ciénaga appears to be restorable. **R**
153. Whitlocky's Ciénaga. Minckley and others (2013). United States, Arizona, Graham County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.56 -109.29; 1,077 m (3,534 ft) elevation. This area currently looks like a playa bottom, and no ciénaga occurs here now. **D**
154. Willow Springs. Sivinski, Robert, pers. comm. (2013). United States, New Mexico, Socorro County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 33.8105 -106.9778; 1,631 m (5,350 ft) elevation. Located approximately 29 km (18 mi) southwest of Socorro. **S**
155. Williamson Valley Ciénaga. Minckley et al. (2013). United States, Arizona, Yavapai County. Aquatic ecoregion (river basin)—Gila. Coordinates: 34.825 -112.633; 1,393 m (4,571 ft) elevation. Located 33.8 km (21 mi) northwest of Prescott, this site is in a large agricultural operation with an adjacent 6.4 km (4 mi)-long riparian ribbon that appears on Google Earth to end where large fields are wet. There does appear to be a small body of water near the site and with all the farming, surely there is water available for restoration. **R**

The following seven waters are recognized as ciénagas on earlier lists but are better thought of as wet, high mountain meadows, above 2,100 m (7,000 ft). We note them below to apprise the reader that we are aware of their existence and that they have been excluded from our list above and not overlooked.

- Barfoot Springs. Minckley et al. (2013). United States, Arizona, Cochise County. Aquatic ecoregion (river basin)—Gila. Coordinates: 31.917 -109.279; 2,515 m (8,250 ft) elevation.
- Bear Wallow Ciénaga (also known as: locally Bill Lewis Cienaga, Jennings, and High Peak Ciénaga). Minckley et al. (2013). United States. Aquatic ecoregion (river basin)—Gila. Coordinates and elevation unknown. This is a small marshy area in Catron County, NM, just east of Bear Wallow Mountain, that still has marsh and aquatic vegetation.
- Bush Valley Ciénaga (also known as: Alpine Cienaga). Hayes, Frank, pers. comm. (2014). United States, Arizona, Apache County. Aquatic ecoregion (river basin)—Gila. Coordinates: 33.835954 -109.125583; 2,418 m (7,933 ft) elevation.
- Ciénaga—Unnamed. (Source unknown.) United States, New Mexico, Catron County. Aquatic ecoregion (river basin)—Gila. Coordinates: 33.6696 -108.5691; 2,725

m (8,939 ft) elevation. This was thought to be a boggy part of the Tularosa Creek valley near Aragon, NM, east of Reserve, but these coordinates may be incorrect. This point is too high, too steep, and with no wetlands.

- Highwater Ciénaga. Minckley et al. (2012). United States, Arizona, Graham County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.703 -109.884; 3,125 m (10,253 ft) elevation. Southwest of Safford, this is a high mountain meadow.
- Ciénaga Gregorio (also known as: St. Gregorio Lake and San Gregorio Reservoir). Pearce (1965) and Julian (1996). United States, New Mexico, Rio Arriba County. Aquatic ecoregion (river basin)—Upper Rio Grande—Bravo. Coordinates: 36.04 -106.85; 2,874 m (9,428 ft) elevation. Julian details the history of Gregorio Lake, 96.6 km north of Albuquerque, 9.7 km east of Cuba in Rio Arriba County. Once considered a ciénaga, the lake was created when the Cuba Water Users Association dammed Cienaga Gregorio, the name derived from a sheepherder who worked in the area before 1900, for irrigation.
- West Hospital Flat Spring. Jones, Cory, Sky Island Alliance, pers. comm. (2013). United States, Arizona, Graham County. Aquatic ecoregion (river basin)—Gila. Coordinates: 32.666 -109.876; 2,750 m (9,022 ft) elevation. This wetland is located in the Pinaleno Mountains in Graham County, AZ, just above Hospital Flat Campground along the Swift Trail (SR 366). The site consists of wet-meadow habitat with three narrow stream channels running through it.

Appendix C. Aridland Ciénagas and Springs in the Mid-19th-Century North American Southwest

The 64 spring and ciénaga sites identified here are located in the southeast portion of Arizona, southwest New Mexico, west Texas, and south of the international border, as shown on Captain Allen Anderson's 1864 Map of the Military Department of New Mexico and Lieut. Wheeler's Expedition, nach New-Mexico & Arizona, 1873, both of these found in Peter L. Eidenbach's (2012) *An Atlas of Historic New Mexico Maps, 1550–1941*, and several other sources. Anderson was the Acting Engineer Officer under the direction of Brigadier General James Carleton during the period when Carleton's field commander Kit Carson captured and interned the Mescalero Apaches and Navajos at Bosque Redondo. Wheeler mapped most of the lands west of the hundredth meridian for the U.S. Army between 1872 and 1884.

The purpose of this list is to document the occurrence of springs and ciénagas along travel routes in the International Four Corners Region at the time of the movement of American settlers westward. It is impossible to know either the number of springs or those that supported ciénagas because of their large numbers and because state-level inventories have not been completed, fewer than half of the known springs are named, springs are poorly studied, and thousands

no longer have water. The named springs in the western United States have been inventoried by state in Stevens and Meretsky (2008), with a total of 29,862 *ojos* (springs).

Waters bearing the words *Ojo*, Spr., Spring, Springs, and Cienaga reflect the term listed in the maps where we found them. The listing sequence of 1 through 64 is more or less from north to south or toward the international border, and from there, from west eastward. We have not included lagunas, rivers, creeks, streams, or other water features that appear not to meet the potential or criteria for a ciénaga or for a ground-fed water feature that may have formerly been a ciénaga. Only 8 of the 61 waters bear the name *ciénaga*, yet some—likely a good many—of the springs supported ciénagas.

It would require a tremendous effort and expense to assess both the desiccated and the wet remaining *ojos* in order to determine which springs may have supported ciénagas. Although most aridland ciénagas are associated with springs and other groundwater discharge, not all springs support ciénagas. At the time of the massive migration west, travel routes were dotted with *ojos* and an uncertain number of co-occurring ciénagas surely were already dewatered, unappreciated, or overlooked, and were never recorded by cartographers. It is unlikely that the number of *ojos* that supported ciénagas will ever be known, but there were certainly more than the 155 named ciénagas listed on the working inventory, Appendix B.

1. Ojo de los Cojotes (west of Tucson, AZ)
2. Ojo de Buzany (south of the int. border, AZ/NM line, SO)
3. Ojo de San Ignacio (south of int. border, east of Buzany, SO)
4. Cienegas de los Pimas (southeast of Tucson, AZ)
5. San Pedro Sprs. (southeast of Pimas, AZ)
6. Bear Spr. (southeast of Fort Grant, AZ)
7. Dove Spr. (south of Bear Spring, AZ)
8. Chamelcon Spr. (south of Dove, AZ)
9. Spring, unnamed (southwest of Fort Bowie, AZ)
10. San Bernardino Spr. (south of int. border, below Fort Bowie, SO)
11. Cienega Bonita (north of Fort Bowie, AZ)
12. San Luis Spr. (south of int. border, west of San Bernardino, SO)
13. Mangus Spring (north of Fort Tulerosa, NM)
14. Curizo Spr. (north of Fort Tulerosa, south of Mangus, NM)
15. Ojo del Lobo (northwest of Forts Conrad & Craig, NM)
16. Wolf Spring (northeast of Lobo, NM)
17. Horse Spring (south of Lobo, NM)
18. Gallo Spring (northeast of Fort Tulerosa, NM)
19. El Creston Cienega (south of Lobo, NM)
20. Cienega del Datil (south of Creston, NM)
21. Cienega del Guiso (north of Fort West, NM)
22. Cienega, unnamed (south of Fort West, NM)
23. Ojo, unnamed (south of Burro Mt., NM)
24. Coyote Spring (south of Cienega Spring, NM)
25. Emory's Spr. (north of border in the Bootheel, NM)

26. San Francisco Spr. (south of int. border, southwest of Emory's, SO)
27. Ojo de Luera (west of Fort Conrad, NM)
28. Cienega de los Alamos (south of Luera, NM)
29. Ojo de los Mosquitos (across int. border, east of Bootheel, CH)
30. Carrizalillo Spring (north of int. border, east of Bootheel, NM)
31. Ojo del Pinesco (west of Fort McRae, NM)
32. Ojos Calientes (west of Fort McRae, NM)
33. Spr., unnamed (south of Pinesco & Calientes)
34. Ojos Calientes (same name, north of Apache, NM)
35. Cienega del Apache (north of Fort Horn, NM)
36. Ojo del Berenda (south of Apache, north of Fort Horn, NM)
37. Cook's Springs (at Fort Cummings, NM)
38. Ojos de los Adjustments (below int. border, southwest of Las Cruces, CH)
39. Sulphar Spring (west of Fort Craig, NM)
40. Nogal Spr. (south of Fort Craig, NM)
41. Ojo del Muerie (west of Fort McRae, NM)
42. Pond of Aleman (south of Fort McRae, NM)
43. Spring, unnamed (southeast of Fort McRae, NM)
44. Mal Pais Spr. (Salt) (east of Fort McRae, NM)
45. San Andres Spr. (north of Las Cruces)
46. Ojo de San Nicolas (north of Las Cruces, NM)
47. Ojo de San Augustine (east of Las Cruces, below Nicholas, NM)
48. Ojo Soledad (east of Las Cruces, south of Nicholas, NM)
49. Spring, unnamed (south of int. border, near El Paso, CH)
50. Perdido Spr. (east of El Paso, TX)
51. Ojo del Cuervo (east of El Paso, TX)
52. Eagle Spr. (east of Fort Guitman, TX)
53. Water Holes (east of Fort Guitman, TX)
54. Van Horn's Wells (east of Fort Guitman, TX)
55. Water Holes (east of Fort Guitman, TX)
56. Springs, Dead Man's Hole (west of Fort Davis, TX)
57. Spring, unnamed (west of Fort Davis, TX)
58. Spring, unnamed (west of Fort Davis, TX)
59. Leon Spr. (northeast of Fort Davis, TX)
60. Venado Spr. (southeast of Fort Stanton, NM)
61. Captain Pope's Well (north of Fort Davis, NM)

The Upper Gila River Fluvial Geomorphology Project: A History of Geomorphic Change

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Abstract

This paper summarizes the Upper Gila River Fluvial Geomorphology Project, which was initiated to investigate the cause of channel change and property damage during extreme floods of the 1970s, 1980s, and 1990s on the upper Gila River in southwestern New Mexico (Wittler and Levish 2004). The project was interdisciplinary in nature, designed to approach the problem from hydrologic, geomorphic, and engineering perspectives. The geomorphic investigations from the study are the focus of this paper. Results indicate that conditions in the headwaters are not the primary cause of geomorphic change downstream of the Upper Gila Box. Analyses of historical aerial photography show that the Gila River channel widens during periods of multiple large floods to accommodate higher discharges and narrows during periods of few large floods. This pattern is accentuated by levee building and the reoccupation of channeled areas for agriculture during periods of low flow. High variability exists in channel width and position in the alluvial valleys of the Gila River. Although many channel positions that are documented are not new, there are several cases where they are unprecedented in the historical record. A greater number of unprecedented channel positions were formed between 1980 and 1996 than in any other time interval in the historical period. Since external factors such as changes in runoff and sediment delivery from the upper Gila River Basin do not appear to be responsible for geomorphic change in the alluvial valleys, local factors must be considered. These factors include levee and diversion dam construction, bank protection, and tributary alluvial fan development. Historical channel width measurements and geomorphic mapping suggest a relationship between local factors and geomorphic change along the upper Gila River in New Mexico.

Introduction

Between 1970 and 2000, landowners along the Gila River experienced a substantial amount of property erosion during large floods (Klawon 2002; Levish and Wittler 2004). Concern arose regarding whether the river was inherently

unstable or whether conditions in the upper watershed were causing the geomorphic change observed in valleys along the upper Gila River in southwestern New Mexico (e.g., Baker et al. 1994; Covington and Moore 1994; Ohmart 1995; Boucher and Moody 1998). The purpose of our research was to provide an understanding of the fluvial geomorphology and to explain geomorphic change documented along the upper Gila River between 1935 and 2001 in the Virden, Redrock, and Cliff-Gila Valleys. To accomplish this goal, we collected data and conducted analyses of historical changes in river plan form, historical trends in hydrology, historical and pre-historical sediment delivery from the upstream drainage basin, and analysis of channel stability and sediment transport (Klawon and Wittler 2001; England 2002; Klawon 2002; Levish 2002; Levish and Wittler 2004; Wittler and Levish 2004). These analyses represent the majority of work that was part of the larger Upper Gila River Fluvial Geomorphology Project, which was conducted between 1999 and 2004 for the upper Gila watershed in Arizona and New Mexico (Wittler and Levish 2004). This study is broad in scope, seeking to understand the major processes that control the observed fluvial geomorphology. Through this understanding, it is possible to make better-informed decisions regarding river management along the upper Gila River corridor.

The hypotheses for the cause of geomorphic changes along the Gila River in Cliff-Gila, Redrock, and Virden Valleys fall into two categories. The first category includes factors outside the study reach, the most important of which are changes in the characteristics of runoff or sediment delivery from the upper Gila River drainage basin. The second category includes factors within the study reach that influence the morphology of the Gila River. The most important local factors include modification of the river through anthropogenic constructs including levees, bridges, and diversion structures. The hypotheses are stated as follows (Levish and Wittler 2004):

1. A change in the upper Gila River drainage basin characteristics has resulted in increased runoff and sediment supply or a change in runoff and sediment transport characteris-

tics. This change in hydrologic characteristics has resulted in geomorphic change in the alluvial valleys.

2. A change in local characteristics of the river has resulted in geomorphic change. This type of local modification would consist of levee construction and subsequent failure, flow redirection by levees, and reduced sediment transport resulting from levee construction.

Study Areas

The upper Gila River Basin is located in southeastern Arizona and southwestern New Mexico. Within the state of New Mexico, the upper Gila River flows southward from its headwaters in the Gila Wilderness area in Catron County, New Mexico, southwest through Grant County, Hidalgo County, and the town of Virden (Fig. 1). As it flows through the alluvial valleys, the Gila River has a single channel form at low flow that transitions to a braided channel form with multiple threads at higher flows (discharges greater than about 500 cubic feet per second [cfs]). During extreme floods, flow fills the entire channel and may spill into overflow channels in floodplain areas. Five significant tributaries enter the Gila River upstream of Cliff, New Mexico: the West, Middle, and East Forks of the Gila River; Sapillo Creek; and Mogollon

Creek. Main tributaries between Cliff and Virden include Bear, Duck, Sycamore, Mangas, and Blue Creeks. Elevations in the drainage basin range from nearly 3,350 m at the crest of the Mogollon Mountains in the Gila Wilderness area to 1,174 m at the western boundary of the study area (Arizona-New Mexico state line).

In New Mexico, study areas along the upper Gila River were located within the Upper Box, Cliff-Gila Valley, Redrock Valley, and Virden Valley, since these areas were considered most important for documenting and understanding historical geomorphic change along the upper Gila River. The Upper Box begins downstream of the confluence of the Gila River and the East Fork Gila River near the Highway 15 bridge. This reach extends approximately 59 km, ending in the Cliff-Gila Valley (Fig. 1). The river has an average gradient of 0.0045 m/m in the canyon. The 29 km reach of the Cliff-Gila Valley begins at the downstream end of the Upper Box, near Mogollon Creek (USGS station 09430500) and ends near Ira Canyon, a left bank tributary (Fig. 1). The mean sinuosity in the Valley is roughly 1.29 m/m. The river has an average gradient of roughly 0.0028 m/m in the Valley. The Redrock Valley reach is about 25 km long, ending below Blue Creek (USGS 0943200) near Virden, New Mexico. The mean sinuosity in Redrock Valley is about 1.23 m/m with an

average gradient of 0.0036 m/m. The 12.5 km Virden Valley reach begins at the mouth of the Lower Gila Box near Canador Peak and ends at the New Mexico-Arizona state line. The mean sinuosity in Virden Valley is 1.10 m/m and the average gradient is 0.0040 m/m.

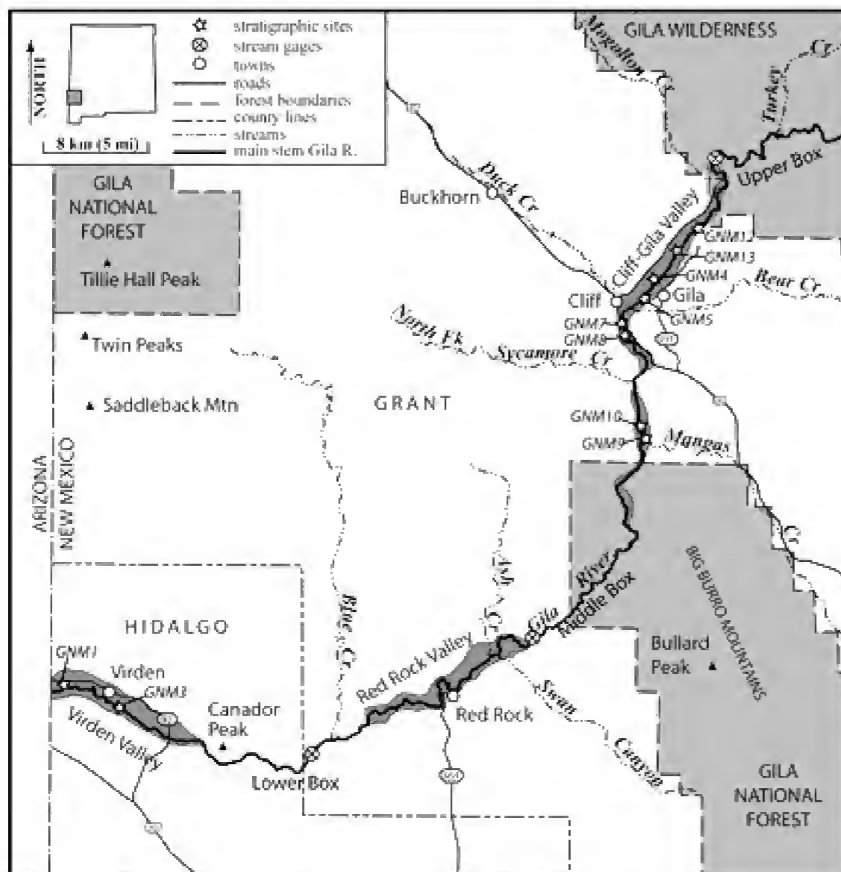


Fig. 1. Study area location. The study area is located in southwestern New Mexico and focuses on the alluvial valleys of the Gila River. The alluvial valleys, outlined in gray, include Virden Valley, Redrock Valley, and Cliff-Gila Valley. The river in between these valleys flows through steep and narrow canyons, termed the Middle and Lower Boxes.

Methods

Historical Aerial Photo Acquisition

Historical aerial stereo photographs were acquired for every decade between 1930 and 2000 (Table 1) with the exception of the 1940s. The aerial photographs were acquired to investigate channel changes and other changes along the upper Gila River corridor. The aerial images were acquired from various government agencies and private vendors. Images were acquired for Virden Valley, Redrock Valley, and Cliff-Gila Valley.

Measurements of Historical Channel Widths

Channel width measurements provide a quantitative means for comparison of the Gila River channel among different years. The spacing of measurements was based on previous studies by Burkham (1972) and Hooke (1996) of channel changes on the upper Gila River, Arizona, where channel width measurements were made approximately every kilometer. The channel widths were measured in the same locations in each set of aerial photographs by

Table 1. List of historical aerial photographs used in the Upper Gila River Fluvial Geomorphology Study, New Mexico.

Year	Date(s)	Agency/Vendor ¹	Scale	Film type ²	Coverage
1935	unknown	NARA (Fairchild)	1:31680	B/W	All
1950	9/1950	NARA (Unical)	1:39996	B/W	Cliff-Gila
1953	11/23–25/1953	AMS	1:54000	B/W	
1956	7/03/1956	Whittier (Fairchild)	1:24000	B/W	Cliff-Gila
1965	11/30/1964 2/19/1965 2/20/1965	ASCS	1:20000	B/W	Viriden, Redrock, Cliff-Gila
1973	4/06/1973	NASAAM	1:30000	B/W	All
1975	8/30–31/1975	BLM	1:31680	CLR	All
1980	11/2–3/1980 11/5–7/1980 8/21/1981	BLM	1:31680	CLR	All
1984	10/08–10/1984	USGS	1:26887	CLR	All
1995	5/18/1995	PWT	1:18000	B/W	Cliff-Gila
1996	9/28/1996 10/10–11/1996	USGS	1:40000	CIR	Redrock, Cliff-Gila
1998	5/23–25/1998	USGS	1:40000	B/W	Viriden
2001	3/04/2001	USBR	1:10000	B/W	All

1. Agency/Vendor information:

AMS Army Map Service (USGS)
 ASCS Agricultural Stabilization and Conservation Service
 BLM Bureau of Land Management, Denver
 NARA National Archives and Records Administration
 NASAAM National Aeronautics and Space Administration, Ames
 (USGS) PWT Pacific Western Technologies
 UNICAL National Archives and Records Administration
 USBR Bureau of Reclamation (Horizons Aerial Photography)
 USGS Geological Survey
 Whittier Whittier College Fairchild Collection

2. Aerial Photograph Film Type: B/W black and white CIR color infrared CLR color

establishing points from which a width measurement was made perpendicular to the flow direction in the photograph (Klawon 2002). Measurement points were chosen in places such as road intersections or bedrock knobs that could be easily relocated on each set of aerial photographs. Using this method, the geographic location of channel measurements for different years remains constant regardless of changes in channel position. Eleven measurement points were established in Viriden Valley; 18 points in Redrock Valley; and 33 in Cliff-Gila Valley. Width measurements were not made in the Upper Box because it is a narrow bedrock canyon with low potential for lateral channel change. For each point, two channel width measurements were made:

(1) *Active channel width*: the part of the channel that was reworked by recent flows at the time of the aerial photography.

(2) *Flood channel width*: the part of the channel clearly

inundated by the largest-magnitude flows during the period between each measurement set. These widths appeared to be the actual channel width during floods, not the result of lateral migration. Where levees were built to protect structures or land from erosion and damage along the river, the allowable flood width between levees was measured for the flood channel width. Following a large flood where levees were destroyed or damaged, the width of the channel formed by the recent flood was measured. In a few areas, plowing and leveling of fields following a flood obscured the evidence of channel modification. In these cases the flood channel width was inferred from adjacent plots that had not been obscured by anthropogenic modifications.

Statistics were generated for each measurement point to analyze the temporal variability in width. Channel width measurements were also analyzed by photograph year and compared to the hydrology along the Gila River and by

study reach in order to compare changes among the valleys. Although both active channel width and flood channel widths were measured, this paper discusses only the flood channel width measurements. River sections with high variability in channel width were utilized as case studies (Klawon 2002). Two of the case studies are discussed in subsequent sections of this paper.

Geomorphic Mapping

Geomorphic mapping combined aerial photo interpretation and field validation of geomorphic features, soil/stratigraphic descriptions, and radiocarbon analyses to provide a long-term picture of river behavior. Since the majority of geomorphic change occurred between 1980 and 2001 (Klawon 2002), the 1980 aerial photography (US Geological Survey) was used as a reference set for geomorphic mapping in GIS.

The geomorphic map shows spatial relationships between channel patterns along the river corridor and natural and anthropogenic features. Mapped features include vertical bank exposures present in 2000, the geomorphic limit of flood evidence, levees, banklines, historical property loss between 1980 and 2000, and tributary alluvial fans that extend into the main channel of the Gila River. These features were mapped on the topographic and aerial photography products developed during this study and field-checked during field data collection. Rather than focusing on the surficial geology of the area, the geomorphic map delineates the features listed above in order to examine the spatial and temporal relationships between areas of erosion and natural and anthropogenic features. Figures 8 and 10 are examples of the geomorphic map that was developed as part of the Upper Gila River Fluvial Geomorphology Study (Levish 2003).

Soil Stratigraphy

To estimate the age of actively eroding soils, bank exposures were examined at 10 sites between the Arizona-New Mexico state line and the Upper Box (Fig. 1). Soil and sedimentologic characteristics of bank exposures were described following USDA guidelines and standard sedimentary terminology (Tucker 1981; Soil Survey Staff 1993; Birkeland 1999). The degree of soil development provides important information about the relative age of soils developed on alluvial surfaces in the study area. Characteristics such as carbonate and clay accumulations and soil structure develop with time and can be used as indicators of soil age (Gile et al. 1981; Machette 1985; Birkeland 1999). Soils that have been studied extensively (e.g., Gile et al. 1981) provide well-documented soil chronosequences but have insufficient age resolution during the Holocene for correlation. For example, the development of stage I carbonate, which is described in many soils along the Gila River in the study area, spans 100 to 7,000 years in non-gravelly soils of southern New Mexico (Gile et al. 1981, p. 68). It is for this reason that soil characteristics are used to indicate relative age while laboratory analysis is intended to provide quantitative age information.

Radiocarbon analysis provides quantitative estimates for the age of alluvium. Radiocarbon analysis relies on the decay

rate of radiocarbon that was incorporated into the tissue of a once living organism (Trumbore 2000). The most common materials found in fluvial sediments that are collected for radiocarbon analysis are wood, charcoal, and shell. There are numerous problems associated with ages derived using this methodology, but when certain precautions are followed it can provide accurate age estimates for the sediments that compose the terrace. Samples for this study were floated and identified by species (macrobotanical identification or shell identification) and pretreated so that any rootlets, seeds, or other young material that might contaminate the sample could be discarded. Based on the identification, plant materials that could potentially have grown near the site were preferred over materials that could have been transported long distances from the upper watershed. Vegetation in the upland areas includes pinyon pine, juniper, manzanita, shrub live oak, and desert hackberry, among others. Vegetation near the Gila River includes creosotebush, tamarisk, cacti, grasses, mesquite, juniper, yucca, and cottonwood, among others (Gelderman 1970; DeWall 1981). The latter list would be the preferred vegetation to date. It is likely that radiocarbon dates from aquatic gastropod shell will more closely match the timing of flood sediment deposition compared to terrestrial gastropod shell, since aquatic gastropods were likely washed in with the flood sediment whereas terrestrial gastropods would have to burrow into the soil sometime after the flood sediment was deposited. The hard water effect was not accounted for in this study. However, dates from shell appear to be consistent with dates from charcoal and are in stratigraphic order. The soils and stratigraphy observed at these 10 sites were correlated to soils and stratigraphy described for the Gila River in the Duncan Valley in Arizona (Klawon 2003) based on similar soil profile development and soil characteristics such as carbonate accumulation, soil structure, color, and clay accumulations. Therefore, radiocarbon ages obtained from soil profiles in the alluvium of Duncan Valley were used to estimate the age of soils in the alluvial valleys of New Mexico.

Results

Flood channel width data demonstrate a pattern of decreasing width from the 1930s to the 1960s and an increasing width from the 1960s to 1998 (Fig. 2). Between 1998 and 2001, flood channel width decreased. Streamflow data from USGS station 09430500 on the Gila River near Gila, New Mexico, are plotted against channel width data to illustrate patterns between large floods and changes in channel width (Fig. 2). The largest floods on the upper Gila River, New Mexico, prior to 2000 occurred in water years 1941, 1973, 1979, 1985, 1993, 1995, and 1997 (Table 2). The flood channel width appears to have responded to some floods by an increase, but this is not the case for some of the largest floods, such as 1978, due to levee construction between the time of the flood and of the aerial photograph in order to prevent future floods from inundating these areas. Following floods in the 1980s and 1990s, levees were not rebuilt in many locations. This

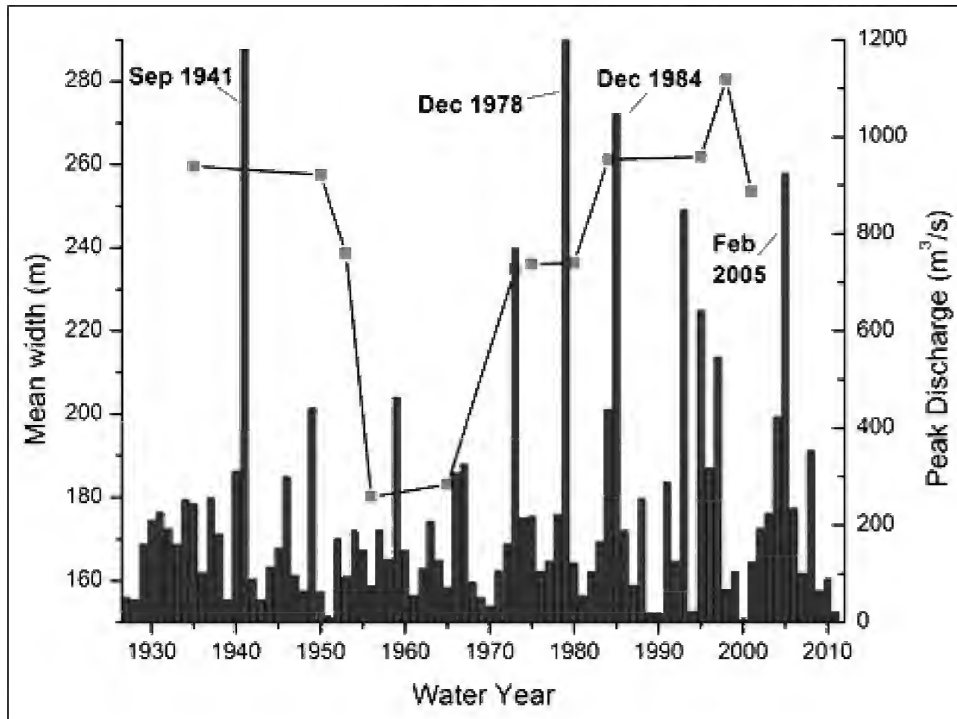


Fig. 2. Average channel width data by photograph year. Flood channel widths are superimposed on the streamgauge record at the Gila River below Blue Creek near Virden, New Mexico.

finding will be explored further in subsequent sections of this paper.

As can be seen in Figure 8 (Location 4), overbank flooding within the boundary defined by the geomorphic limit does not usually result in extensive bank erosion or property loss in areas that are free from levees and other human constructs. In fact, the buried soils observed at many sites show that, to the contrary, floods deposit thin layers of sediment that

result in vertical accretion along the banks. Based on the properties of the soils and stratigraphy at the 10 detailed descriptions and correlation to the alluvium in Duncan Valley (Klawon 2003), it would appear that the majority of actively eroding banks are more than a few hundred years old. In fact, many of the soil and stratigraphic properties observed in the exposed banks suggest that many of the banks currently eroding are more than 500 to several thousand years in age.

The geomorphic reconnaissance of the Upper Box (Levish 2002) allowed for an evaluation of the first hypothesis regarding the source and quantity of sediment as well as a test of possible aggradation or degradation of the Gila River channel bed resulting from a change in sediment delivery and/or transport capacity. The assessment was qualitative because it was based solely on limited field observations and review of aerial photographs. Between the bedrock slopes and the active flood

channel of the Gila River there are often stream terraces along the inner bends of meanders (Fig. 3). These terraces are composed of alluvium that has been stable since pre-19th century based on the presence of developed surface soils or the size of trees rooted on the surface that are not buried by recent sediment. The alluvium is composed of overbank silt and sand deposited by the Gila River during floods. The trees

Table 2. Largest floods at U.S. Geological Survey streamflow gaging stations (modified from England 2002).

USGS Gaging Station No.	Station Name	Drainage Area (mi ²)	Period of Record (Water Years)	Largest Peak Discharge and Date	Second Largest Peak Discharge and Date	Third Largest Peak Discharge and Date
09430500	Gila River near Gila, NM	1,864	1928–2000	35,200 ft ³ /s 12/28/1984	32,400 ft ³ /s 12/18/1978	25,400 ft ³ /s 09/29/1941
09430600	Mogollon Creek near Cliff, NM	69	1968–2000	10,800 ft ³ /s 08/12/1967	10,100 ft ³ /s 12/18/1978	6,430 ft ³ /s 12/28/1984
09431500	Gila River near Redrock, NM	2,829	1905, 1911, 1929–1955, 1963–2000	48,800 ft ³ /s 12/19/1978	40,000 ft ³ /s 09/29/1941	39,100 ft ³ /s 12/28/1984
09432000	Gila River below Blue Creek near Virden, NM	3,203	1927–1997, 1999–2000	58,700 ft ³ /s 12/19/1978	41,700 ft ³ /s 09/29/1941	37,000 ft ³ /s 12/28/1984
09442680	San Francisco River near Reserve, NM	350	1959–2000	9,830 ft ³ /s 10/01/1983	7,870 ft ³ /s 09/30/1983	7,000 ft ³ /s 10/20/1972

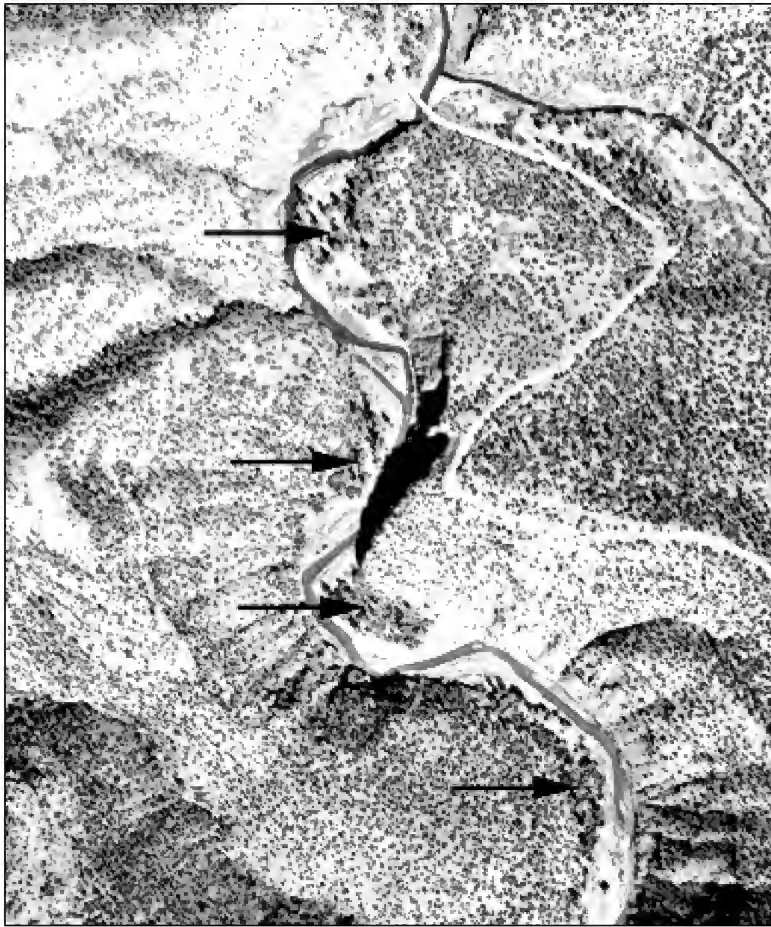


Fig. 3. Aerial photograph of the upstream end of the upper box of the Gila River. Arrows indicate areas of stable alluvium characterized by stands of larger juniper, cottonwood, walnut, and pine trees.

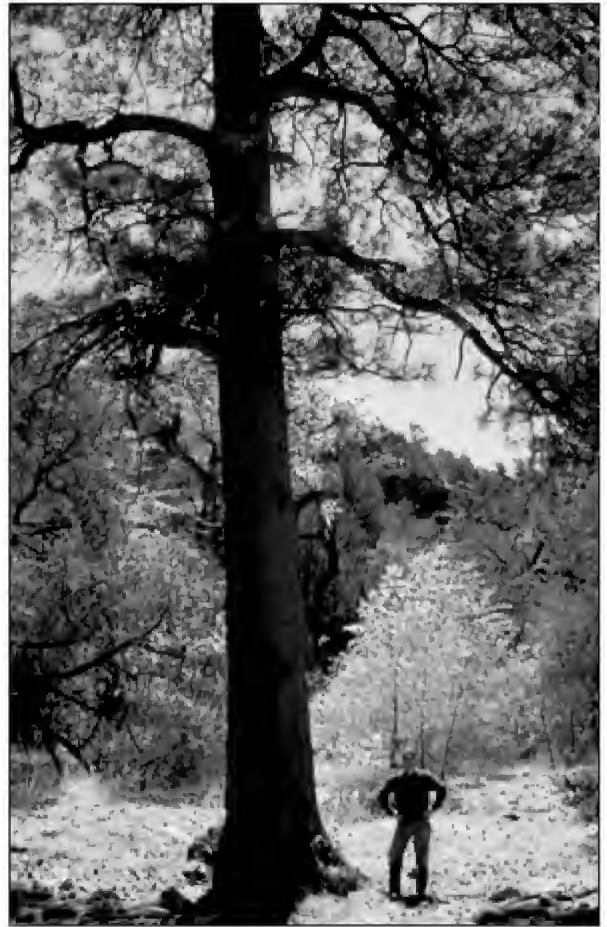


Fig. 4. Large pine tree rooted in Gila River alluvium in the upstream portion of the Upper Box of the Gila River.

are typically large juniper, cottonwood, walnut, and pine (Fig. 4; Levish 2002).

Numerous sycamore (*Platanus wrightii*, Platanaceae) trees are rooted at an elevation near that of the current flood channel. Although no specific information about the age of these trees was developed as part of this study, these long-living species may predate the advent of grazing and fire suppression documented in this region throughout the 19th and 20th centuries (e.g., Rixon 1905; Leopold 1924; Aldon 1964; Boucher and Moody 1998). This could be verified through dendrochronological study of trees growing on the stream terraces and sycamore trees growing in the active flood channel. This would establish minimum ages for the stabilization of alluvial surfaces. Further supporting this conclusion are the truncated alluvial fans found at the mouths of many tributaries (Fig. 5), including those at the mouth of Brushy Canyon, Brock Canyon, Watson Canyon, Turkey Creek, and Hidden Pas-

ture Canyon (Fig. 6). In each case, the toes of these alluvial fans are truncated to a height that corresponds to the stage of the largest historical floods (Levish 2002). This relation-



Fig. 5. Truncated tributary alluvial fan in the upstream portion of the Upper Box of the Gila River.

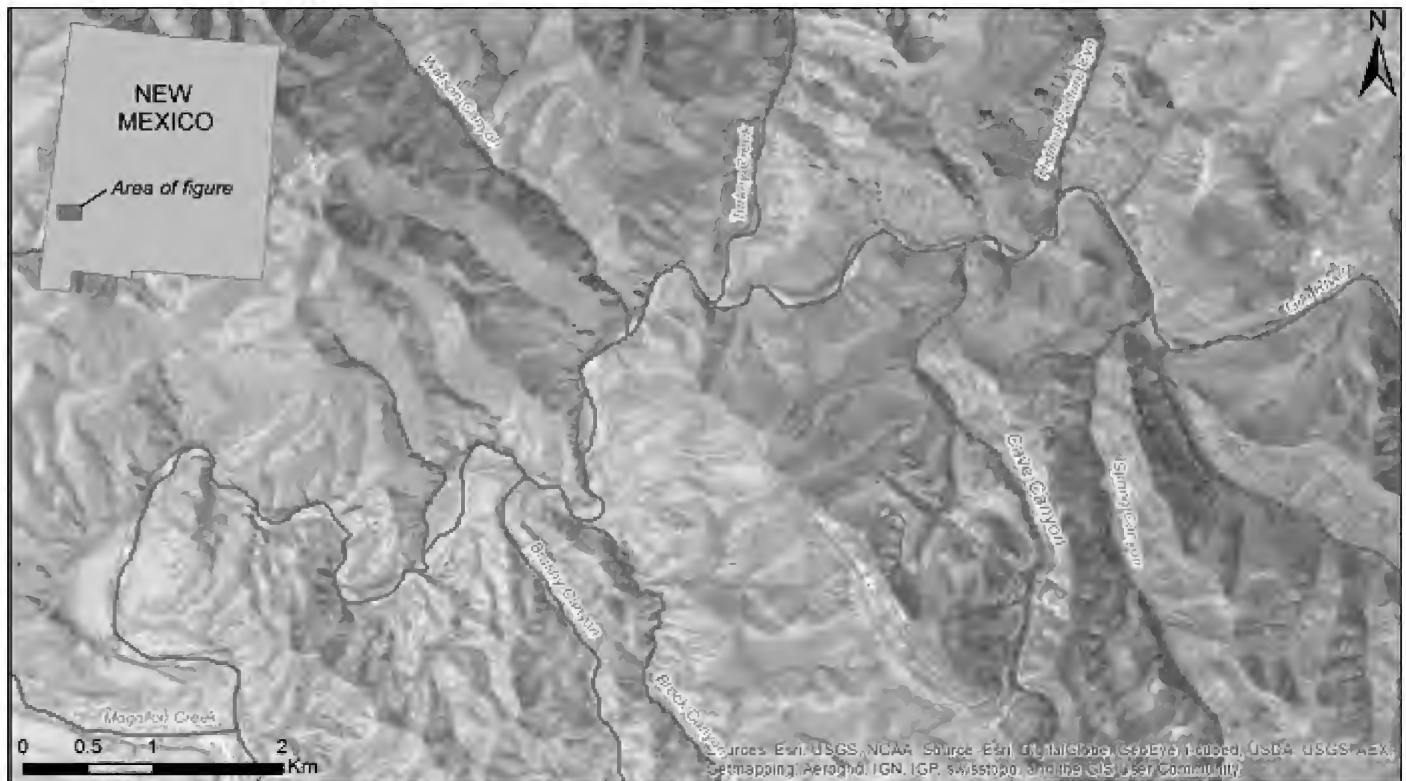


Fig. 6. Location of tributaries in the Upper Box of the Gila River.

ship would not be present if there had been a recent, major change in the mean bed elevation of the Gila River, such as aggradation from recent sediment pulses into the lower valleys.

Discussion

Field reconnaissance shows that there is a record of stable geomorphic surfaces that bound the Gila River in the Upper Box, predating 19th- and 20th-century land use changes (Levish 2002). Field observations did not reveal any major change in bed elevation such as recent burial of large trees from a sediment pulse or degradation of the channel bed, which would isolate geomorphic surfaces from river processes. This record of 20th-century channel stability in the Upper Box places doubt on the hypothesis that changes in the upstream watershed are a major cause of geomorphic change from the downstream end of the Upper Box to the Arizona state line. Based on this reconnaissance, the Gila River in the Upper Box has been stable over at least the historical period, and possibly much longer. In this case, stability of the river is defined as no major unidirectional change in bed elevation during the 20th century. A change in sediment delivery of a magnitude sufficient to cause major geomorphological change in the alluvial valleys of the upper Gila River in New Mexico should be apparent in the geomorphic record of the Upper Box. Indicators of streambed elevation change include buried geomorphic surfaces, the erosion of once stable geomorphic surfaces by floods, increase or lowering in average streambed elevation, or the stranding of alluvial surfaces due to degrada-

tion. The geomorphic record in the Upper Box failed to present any of these indicators.

The hypothesis that local changes in characteristics of the Gila River channel are responsible for the observed geomorphic change in the Gila River valleys is supported by the available data. These factors include levee and diversion dam construction, bank protection, and tributary alluvial fan development (Klawon 2002; Levish 2003; Levish and Wittler 2004). Historical channel width measurements and geomorphic mapping reveal the close correlation between levee construction and subsequent failure and geomorphic change along the Gila River in New Mexico (Levish and Wittler 2004; Wittler and Levish 2004). Levees constructed along rivers eliminate floodplain storage of floodwater, decrease flood-channel sinuosity, decrease sediment transport resulting in aggradation, and redirect flow. Most of the levees along the upper Gila River were not engineered and fail during large floods due to poor design. When a levee fails, flow exits the main stem nearly perpendicular to the levee and is directed onto the floodplain, which usually results in catastrophic property loss. Since the levees artificially raise the stage of the floodwater, the water flowing from a levee breach generally has tremendous energy compared to normal overbank flows (e.g., Tobin 1995; Jacobsen and Oberg 1997). Once behind the levee, the water must find a return path to the main channel. This return path also acts as an effective flow redirection and can propagate erosion and levee failure downstream. Intact levees can effectively redirect flow. This redirected flow can cause substantial erosion on an opposite bank, which can then be propagated downstream through the erosion of alternating bends.

Diversion structures in the Gila River in New Mexico, on the scale of the diversion structure near Virden, New Mexico, generally impact channel morphology both upstream and downstream of their locations (Klawon 2002; Levish and Wittler 2004). Storage of sediment behind the diversion structure causes aggradation of the channel bed upstream of the diversion as well as sediment starvation downstream of the diversion. The extent of aggradation is controlled by the height of the structure and the local slope of the river. The aggradation results in lateral instability of the river channel and a potential for bank erosion upstream and downstream of the structure (Levish and Wittler 2004). The orientation of diversion structures to the channel flow direction at high flows can also be a factor in the erosion of streambanks. If the structure is oriented at an angle to the high flow channel it will aim the flow at a bank downstream, which will likely result in bank erosion and propagation of erosion to banks farther downstream of the diversion. While impacts from diversion structures can be observed along the upper Gila River in New Mexico, it should be noted that their impacts are on a much smaller scale than those along the upper Gila River in Safford Valley, Arizona, because fewer large diversion structures exist along the upper Gila River in New Mexico. Smaller berms constructed with earth or other materials in the channel to divert water for irrigation have more localized effects and tend to breach during floods that are smaller than the extreme floods in the hydrologic record.

In some areas of the Virden Valley, channel change appears to be the result of progradation of tributary alluvial fans into the main river channel, some as a result of the channelization of tributaries. Observations of alluvial fan morphology reveal that in the wider portions of the alluvial valleys, the alluvial fans are built on floodplain surfaces, where tributaries drop their sediment load, especially the larger fractions, at the intersection with the main stem floodplain and far from the main stem channel in most cases. Straightening and channelizing the tributary channels to the confluence with the main stem channel increases their slope, which increases sediment transport and results in a greater volume and larger size distribution of sediment reaching the main stem and its low flow channel. Observations indicate that the main stem flows are somewhat unable to fully mobilize and transport these sediments. The result is an accumulation of sediments in the main stem channel and the disruption of conveyance. In addition, the sediments usually accumulate at the mouth of the tributary, shunting the main stem flow to the opposite bank.

In the Cliff-Gila Valley upstream of Bear Creek, 12 major sediment control dams built prior to 1965 on tributaries limit the amount of sediment reaching the main stem Gila River from local tributaries. Only a few tributaries have been channelized from the tributary canyon mouths to the confluence with the main stem and reach the Gila River; however, these tributaries also have sediment control dams upstream of the channelized reaches. Larger tributaries that are not dammed include Spar Canyon near the upstream end of Cliff-Gila Valley and Bear Creek downstream of Gila, Arizona. These two

tributaries have the potential to deliver significant amounts of sediment to the Gila River and thus may play a role in controlling main stem channel position.

This study has shown that high variability exists in channel width and position in the alluvial valleys of the Gila River in south-central New Mexico (Klawon 2002). Although many channel positions that are documented are not new, there are several cases where they are unprecedented in the historical record. It is also apparent that more unprecedented channel positions were formed between 1980 and 1996 than in any other time interval in the historical period (Klawon 2002). Flood channel widths in recent decades (1980s to present) are similar to or slightly larger than 1935 flood channel widths for the Gila River during the period of study. This demonstrates that the Gila River flood channel can readily adjust its width to accommodate the largest flows. Trends in flood channel width data appear to coincide in general with the hydrologic record of streamflow on the Gila River. Decreases in average flood channel width occur during periods of few large floods (1950s to 1960s) and increases occur during periods of multiple large floods. Although the largest increases in flood channel width have followed large floods, such as the 1972 and 1983 floods, other data show no change even following the largest flood in 1978.

The reason for this discrepancy is the placement of levees following large floods and prior to aerial photography. The levees that were constructed or repaired following the 1978 flood, for example, were in place prior to 1980 aerial photography. This is supported by Donegan (1997), who states that the levees were repaired or replaced rapidly following the flood in anticipation of further flooding. The aerial photography shows that levees cut off many of the new channels formed during the 1978 flood. In these locations, the channel width was measured between the levees, as this was the allowable flood width. The combined 1996 measurements from Redrock and Cliff-Gila Valleys and 1998 measurements from Virden Valley seem to be large compared to 1995 Cliff-Gila data (Klawon 2002). Although there is minimal change in Cliff-Gila Valley between 1995 and 1996 and channel width is actually smaller in Virden Valley, channel widths in Redrock Valley are much larger and skew the result. Streamflow records from 1984 to 1998 show that Redrock Valley experienced larger peak flows than Cliff-Gila Valley for many of the largest floods. This may account for the large increase in flood channel width in the 1996–98 data. In addition, while damaged levees were repaired or new levees were built in other valleys, constricting the width of the channel, a review of aerial photography from 1996 shows that they were not repaired or built in Redrock Valley. Comparisons between Virden, Redrock, and Cliff-Gila Valleys show that reaches of high flood channel width variability (standard deviation > 60 m) are approximately 10 to 15% more common in Cliff-Gila Valley than in Redrock or Virden Valleys when reach length is taken into account (Klawon 2002).

Similar patterns in channel width have been documented on the upper Gila River in east-central Arizona (Burkham

1972; Hooke 1996; Klawon 2001). In Safford Valley, mean flood channel widths were generally small in the late 1800s. This was followed by an increase in channel width in the early 1900s, which corresponds to a period of frequent large floods. Channel narrowing occurred from the 1920s through the 1960s, a period of few large floods. Other factors such as vegetation growth, levee construction, and agricultural development also promoted channel narrowing during this period. In the 1960s, a period of more frequent large floods began and flood channel widths again increased. Similar patterns have been observed for other semi-arid streams in the Southwest (e.g., Baker 1988), although in the case of the Gila River, the pattern has been accentuated by artificial constriction of the channel.

Additional supporting studies of hydraulic modeling in the alluvial valleys (Wittler and Delcau 2002) and hydrologic analysis (England 2002) were conducted as part of the Upper Gila River Fluvial Geomorphology Study. Although they are not the focus of this paper, these studies also cast doubt on the hypothesis that geomorphic change is the result of some combination of a change in runoff and a change in sediment delivery. These studies demonstrate the lack of strong trends in runoff and precipitation over the past four decades along with no apparent net change in sediment transport capacity and therefore do not lend support to the first hypothesis. Trend analysis using the Mann-Kendall test (e.g., Helsel and Hirsch 1992; Hirsch et al. 1993) was used to investigate precipitation and streamflow data over the past 70 years (England 2002). Significant positive precipitation trends were found in annual, winter, spring, and summer total precipitation at seven sites within and near the upper Gila watershed. However, there was no statistically significant increase in seasonal, annual, or 1-day maximum precipitation at any of the eight stations analyzed for the 1971–2000 period, when the majority of property erosion occurred. There were significant positive trends in 3-day maximum flood discharge at the Gila River near Gila and Gila River near Virden gages. The trends were consistent for the 1931–2000 and 1941–2000 periods. In addition, there were increasing trends in peak flow, daily maximum, and 3-day maximum at the Gila gage for 1931–2000, 1941–2000, and 1951–2000. Notably, there were no significant trends identified for flood discharge quantities at the five gaging station locations for the recent 40-year (1961–2000) or 30-year (1971–2000) periods.

Multi-decadal variations in flood frequency are common in the Southwest (e.g., Webb and Betancourt 1992; Redmond et al 2002; Kiem et al. 2003). This pattern generally displays episodes of frequent large floods followed by episodes of few large floods. These episodes may differ by geographic area and may last few to many decades. It appears that the Gila River has experienced a period of few large floods from the 1930s through the early 1970s bracketed by periods of more frequent large floods, one at the turn of the 20th century and one from the late 1970s through at least the early 1990s (see Fig. 2). The results of the hydrologic analysis by England (2002) indicate that property erosion occurs during periods of

multiple large floods, but there is no positive trend in runoff during the most recent periods (about 1960–2000). In other words, floods have not continued to increase in magnitude with each subsequent decade.

Case Studies

Case Study 1: Seeds of Change

The Seeds of Change reach is near the upstream end of Cliff-Gila Valley, approximately 5 to 7 km upstream from Gila, New Mexico. Between 1935 and 1950, agricultural encroachment and levee building narrowed the channel; the most prominent levee was built at the upstream end of the reach and reduced the flood channel width by approximately one third to one half (Fig. 7). Channel straightening and levee construction further narrowed the channel and cut off meanders between 1950 and 1953. The channel widened by 1975, eroding some of the levees constructed in the 1950s. The 1978 flood further widened the channel; levees were replaced or repaired in the same locations, which cut off some new sections of channel formed by the 1978 flood. Levees built following the 1978 flood were mostly destroyed by 1996; in some cases, according to the historical aerial photography, the channel positions were unprecedented. New levees were built in some locations between 1984 and 1996, such as near the old Bennett farm, to protect agricultural land. In this case, berms, a pilot channel, and a backwater area were created in an attempt to stabilize the reach. The present (2001) channel is very similar to the 1996 channel.

The pattern of erosion seen at the Seeds of Change Farm typifies the channel changes that result from levee breach and return flow. The pattern is generally asymmetrical in the downstream direction with a sharp bend where the return flow attempts to reenter the main channel (see Location 1; Fig. 8). The property loss in this area is clearly associated with levee construction following the December 1978 flood. The pattern of erosion also demonstrates the downstream propagation of flow redirection resulting from levee failure. Erosion at Location 2 would appear to be a direct result of the erosion and subsequent flow redirection at Location 1, in that bank erosion resulting from levee failure at Location 1 directs the flow perpendicular to the former flood channel. The flow deflects off the bank on the east side of the river, which is protected by higher geomorphic surfaces, and migrates toward Location 2. Locations 3 and 4 also appear to be eroded due to the downstream propagation of flow redirection from Location 1. In this case the banks on the east side of the river are fortuitously not eroded due to the presence of levees on high geomorphic surfaces, alluvial fans, or for some other reason. For instance, east of Location 4, flood flow over the alluvial surfaces leaves obvious evidence of erosion and deposition. However, the flow does not result in property loss because it can spread over the surface. The alluvial fan on the west side of the river at the mouth of Winn Canyon (Location 4), disrupts this pattern of downstream propagation by forcing the flow over the east bank and maintaining the same flood flow pattern as prior to levee construction.

Fig. 7. Historical aerial photography from the Seeds of Change reach.

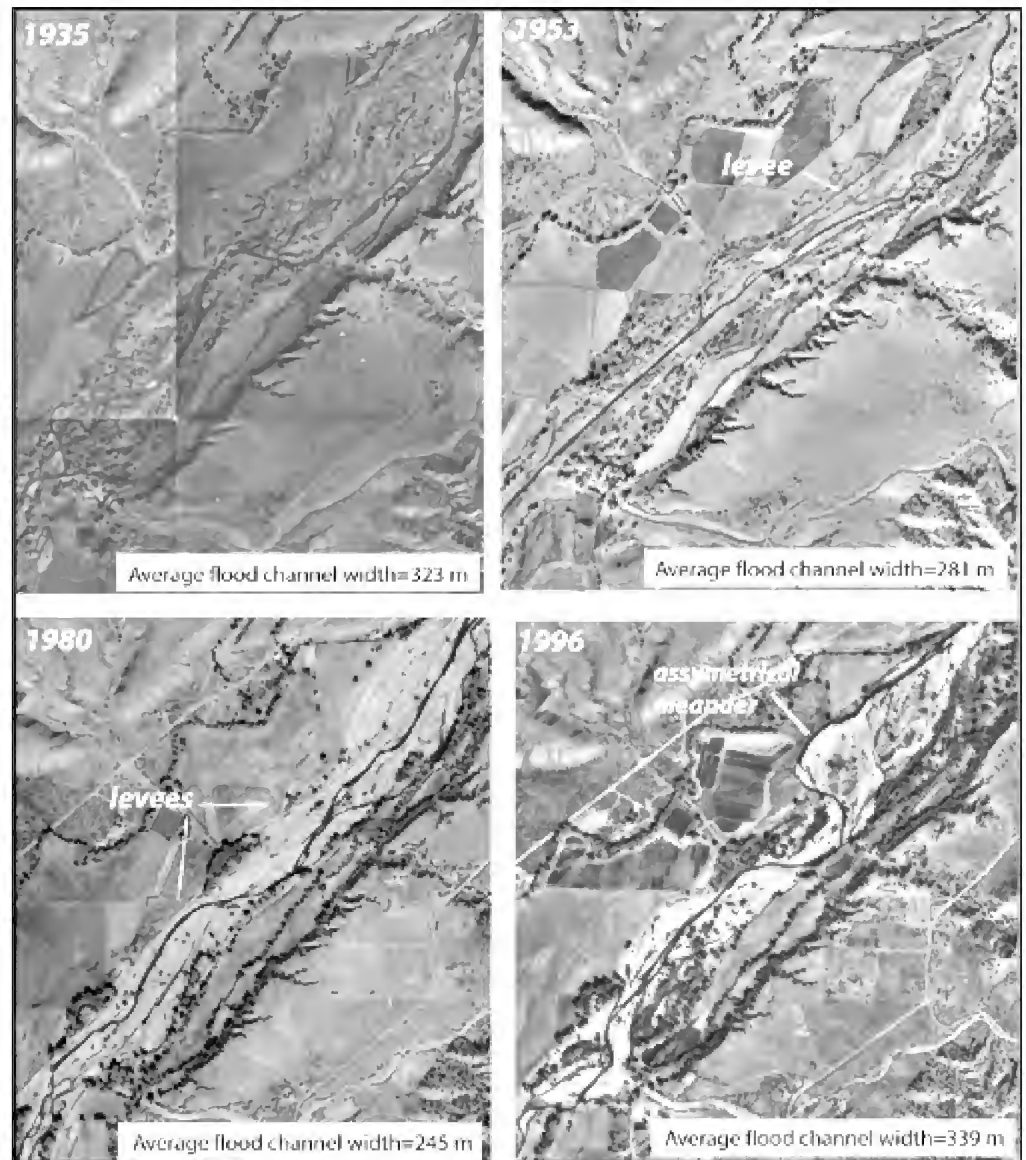
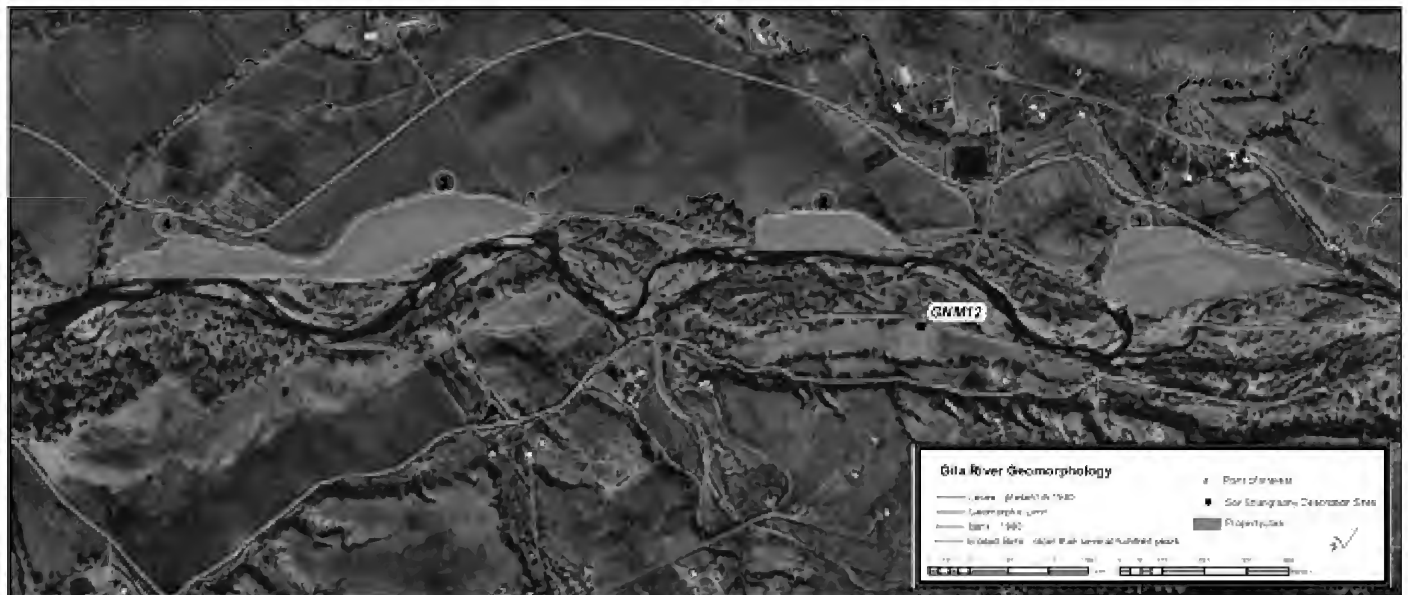


Fig. 8. Geomorphic mapping near the Seeds of Change farm.



Case Study 2: Iron Bridge

Downstream of the Highway 180 Bridge there is a stratigraphic record of aggradation and there are breaches and flood flow paths that are visible following the failure of these features. At this site, it appears that the levees restricted sediment transport, resulting in aggradation. This aggradation probably raised the elevation of the bed during the 1950s and 1960s and the hydraulic head on the levee. During the 1972 flood, the river breached a levee along the right bank upstream of the Iron Bridge, which resulted in sedimentation and the formation of overflow channels on farmland. During the 1978 flood, the river breached the levees lining the channel, likely by eroding the mid-section or base of the levee, and eroded a large amount of agricultural land along the river (Fig. 9).

Just upstream of the Iron Bridge (old Highway 180 Bridge) and Highway 180 Bridge, levees were constructed prior to 1980 to direct flow under the bridge and protect the bank (Fig. 9). However, the levees had the effect of directing flow at the opposing downstream bank, resulting in significant erosion between 1975 and 1996. This pattern was repeated at successive bends downstream.

Geomorphic mapping in Figure 10 shows erosion and property loss at Locations 12, 13, 14, and 15, resulting from the post-1978 flood levee construction at Location 11 near the Iron Bridge. Construction of the levee at Location 11 effectively redirected flood flow under the Iron Bridge directly at Location 12. The result was a pattern of new meanders nearly out of phase with the previous meanders. This created erosion and property loss through the entire valley near Riverside. At these locations, the Gila River now flows perpendicular to the preexisting banks. The down-

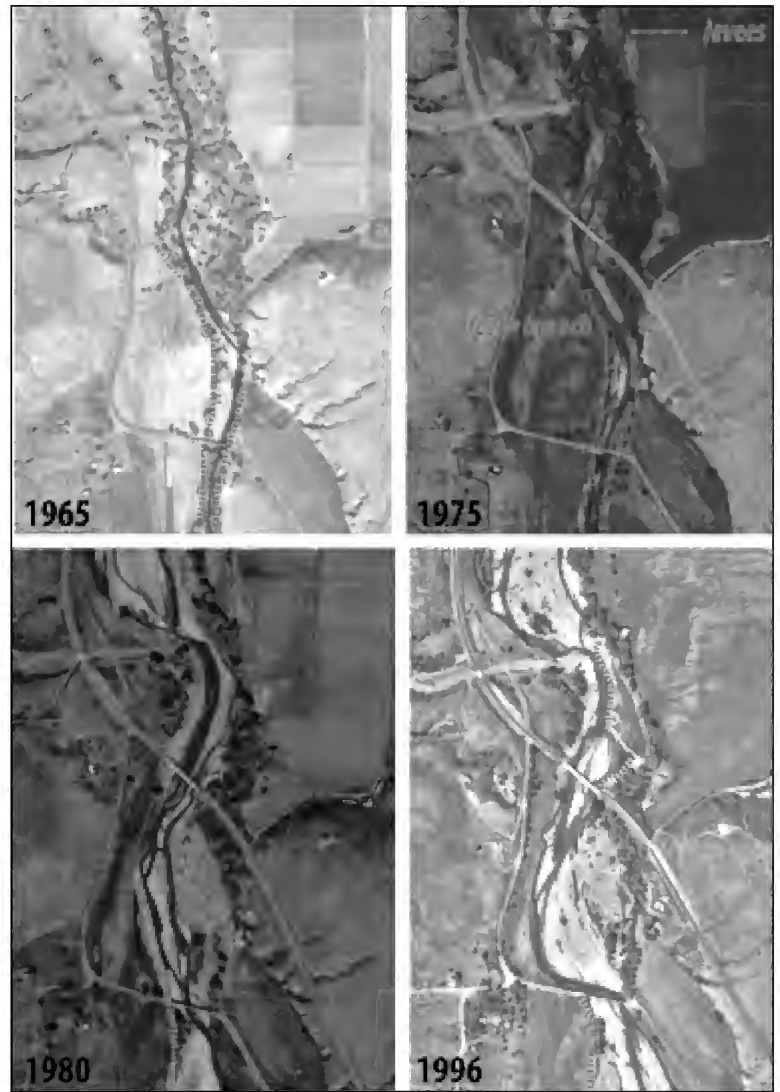


Fig. 9. Historical aerial photography near Highway 180 Bridge.

Fig. 10. Geomorphic mapping downstream of Highway 180.



stream propagation of flow redirection was probably halted by the alluvial fan from Greenwood Canyon that forced the Gila River back into the pre-levee flow direction. Bank descriptions in this reach at GNM7 and GNM8 indicate that these soils have been developing for at least 500 years or longer (Levish and Wittler 2004).

Conclusions

The results of these analyses point toward local controlling factors for the observed historical geomorphic changes along the alluvial valleys of the Gila River in New Mexico. Based on these analyses it appears that in the Upper Box, the Gila River has been dynamically stable both vertically and laterally during the 20th century. Thus, the observed geomorphic changes do not appear to be the results of a system-wide change in sediment yield or a change in hydrology. This conclusion is supported by the data collected for this study (Klawon and Wittler 2001; England 2002; Klawon 2002; Wittler and Levish 2001; Levish 2002; Wittler and Delcau 2002; Levish 2003; Levish and Wittler 2004; Wittler and Levish 2004). Instead, human disturbance of the Gila River, primarily in the form of levee construction, has led to the observed geomorphic change in the alluvial valleys and is itself the most altering geomorphological change in the study reach.

Results from this study show that channel changes are related to large floods on the Gila River. During periods of large floods, channel widths tend to increase, while during periods of few large floods channel widths tend to decrease. This pattern appears to be accentuated by the building of levees, bridges, and other structures as well as agricultural development of land that was previously part of the flood channel. This highlights the important point that the largest floods in the Gila River system have lasting effects that can be observed in channel morphology for decades following their occurrence. Modification of flood flow inside the geomorphic limit is likely to result in eventual property loss. Any modification of flow inside this boundary should be critically evaluated by detailed hydraulic modeling to predict possible unwanted property loss or damage. In most cases, flood channel widths at specific channel locations are variable but not unprecedented in the historical record. Reaches of high variability, however, show that there are multiple locations where recent channel changes are unique in historical aerial photography (Klawon 2002). These types of channel changes are present in all three valleys; examples are presented in the case studies in this paper. Cliff-Gila Valley has experienced more perturbations in the period of study than either Virden or Redrock Valley and with more unprecedented channel positions formed between 1980 and 1996 than at any other time in the historic period.

Since the goal of the study is to understand and document the most important physical processes that shape river morphology, it is probable that some factors have been overlooked in this analysis. When considering any modification of the river or bounding structures, it would be prudent to contrast the intended purpose of the modification with the findings

outlined and supported in this paper, as well as those in the original reports of the Upper Gila River Fluvial Geomorphology Study (Klawon and Wittler 2001; England 2002; Klawon 2002; Levish 2002; Levish and Wittler 2004; Wittler and Levish 2004).

Acknowledgments

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The research presented here is a summary of the Bureau of Reclamation fluvial geomorphology study of the Gila River in New Mexico. The Reclamation study managers are Mary Reece and Vivian Gonzales, Phoenix Area Office (PXA). Co-principal investigators for this study are Dr. Rodney J. Wittler, hydraulic engineer, and Dr. Daniel R. Levish, fluvial geomorphologist, US Bureau of Reclamation.

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A Bryophyte Inventory of the Gila National Forest: An Initial Assessment

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Abstract

Bryophyte research in the Gila National Forest (GNF) of southwest New Mexico began with the collection of 18 specimens by Metcalfe beginning in 1903. There was a paucity of work on bryophytes in the GNF until Allred collected 300 specimens starting in 1997. Kleinman and Blisard began the current bryophyte inventory in 2010 and have collected over 500 specimens, which form the basis of this report. To date we have identified 116 moss species in 28 families and 18 liverwort species in 11 families; four of the mosses and two of the liverwort collections are new state records.

Keywords: mosses, liverworts, Gila National Forest, bryophytes

Introduction

We have worked for four years (2010–2013) to characterize the bryophyte flora of the GNF. Until quite recently, the extent of bryophyte research in the GNF was very limited.

Orrick Baylor Metcalfe was apparently the earliest collector of bryophytes in the GNF. He lived in the Mangas Springs area and was one of Elmer Ottis Wootton's students at the New Mexico College of Agricultural and Mechanic Arts in Las Cruces. Metcalfe concentrated on collecting plants in the Black Range between 1902 and 1904, including the first 18 bryophyte specimens collected from the GNF. Metcalfe collected *Entodon schleicheri* (Schimper) Demeter from the West Fork of the Gila, one of only two collections of this moss known from the GNF.

Other bryologists have visited the area and collected specimens, including A. Barnett (6 specimens from 1938 to 1940), A.M. Harville (3 specimens in 1947), Michael Baad (8 specimens in 1964), Richard Worthington (30 specimens from 1985 to 2000), Thomas Todsen (5 specimens beginning in 1990), and Leila Schultz (8 specimens in 1994). A single collection of *Scleropodium obtusifolium* (Mitten) Kindberg was made by Lewis E. Anderson—this remains the only known collection of this moss from the GNF.

Kelly Allred has collected about 300 specimens from the GNF since 1997. His research into the mosses of the GNF was the most extensive until the current study.

Study Area

With a total area of 1.34 million ha (3.3 million ac), the GNF is a large area in which to conduct a bryophyte survey. The terrain varies from Chihuahuan desert scrubland (1,295 m, 4,250 ft elevation) with its mariola (*Parthenium incanum* Humboldt, Bonpland & Kunth) and creosote bush (*Larrea tridentata* (Sessé & Mocino ex A.P. de Candolle) Coville var. *tridentata*) to the spruce-fir forests of the Mogollon Range, reaching 3,321 m (10,895 ft) in elevation. We included the Gila Cliff Dwellings National Monument in the study area. The Cliff Dwellings are located 71 km (44 mi) north of Silver City and consist of 216 ha (533 ac) of steep cliffs and canyons entirely surrounded by the GNF.

The geography of the GNF can very generally be described as the Gila River, its tributaries, and the mountain ranges and canyons associated with these drainages. The mountain ranges include the Mogollon Range, the Black Range, the Silver City and Pinos Altos ranges, the Tularosa Range, the Burro Mountains, the San Francisco Range, and many smaller ranges.

The geologic history of the GNF is complicated but is dominated by volcanic events with the resulting calderas and lava flows (NPS, n.d.a, n.d.b; Ratte and Gaskill 1975). Volcanic rock dominates much of the landscape in the GNF (New Mexico Geological Society 2008). Alluvial deposits and erosion of the ridges eventually filled low-lying areas with gravels and Gila Conglomerate. Limestone is found in areas of the Black Range and elsewhere. Geologic substrate commonly defines which mosses may be found in an area. For example, within the genus *Grimmia*, some species grow on alkaline substrates such as limestone, while other species grow preferentially on acidic rock such as granite.

At moderate elevations 2,133–2,743 m (7,000–9,000 ft) in the GNF, ponderosa pine forests cover the mountainsides. Below the ponderosa pine forests, pinyon-juniper woodland is common. Over 2,743 m (9,000 ft) elevation, spruce-fir forest predominates. Just as these major elements of the vascular plant flora occupy niches based on temperature, rainfall, humidity, sunlight, and other environmental features, so do the bryophytes. Thus, mosses and liverworts commonly found at lower elevations in the GNF are unlikely to be found on peaks high in the Mogollon Range.

Methods

A research and collection permit was obtained from both the GNF and the Gila Cliff Dwellings National Monument. We began collecting bryophytes in the GNF in 2010 and are continuing to look for new species. Each collection consists optimally of approximately 4 cm² of bryophyte material along with date of collection, location, habitat, substrate, and associated vascular plant species. We have made over 500 bryophyte collections from the GNF to date, including more than 250 from the Gila Cliff Dwellings National Monument starting in March 2011. Kleinman and Blisard examined most specimens initially. Problematic specimens and new species were evaluated by Allred. Experts were consulted when the correct identification was still in doubt. Voucher specimens have been placed in the Dale A. Zimmerman Herbarium at Western New Mexico University (SNM).

As each new species was identified, it was photographed in detail and added to the website gilaflora.com. Gilaflora.com has for the past several years served to document the regional vascular flora and has recently been expanded to include bryophytes.

Moss nomenclature follows Allred (2011). Liverwort nomenclature follows Blisard and Kleinman (2014).

Results

We have identified 116 species of mosses in 28 families and 18 species of liverworts in 11 families. Although we searched diligently, we found no hornworts in the GNF. Hornworts have not been found anywhere in New Mexico. As would be expected for the arid Southwest, the dominant moss family in our area is the drought-tolerant Pottiaceae, comprising more than 20% of the moss flora by species.

Our collections of the mosses *Entodon seductrix* (Hedwig) Müller Hal., *Crumia latifolia* (Kindberg) W.B. Schofield, *Crossidium squamiferum* (Viviana) Juratzka, and *Brothera leana* (Sullivant) Müller Hal. are new state records. *Crumia latifolia* is known from California and Arizona. *Crossidium squamiferum* is known from California, Arizona, Nevada, Utah, and Colorado. Our collections represent a range extension to the east for these mosses, which are known from adjacent states mostly to the west of New Mexico. On the other hand, *Entodon seductrix* is widespread in eastern North America west to Texas. Our collections, therefore, represent a range extension to the west for a moss known from adjacent states to the east of New Mexico. *Brothera leana* was unknown west of the states bordering the Mississippi River valley. Our collection from a dead tree stump on the north flank of Signal Peak in the Pinos Altos Range represents a disjunct population (Kleinman et al. 2011). It is also

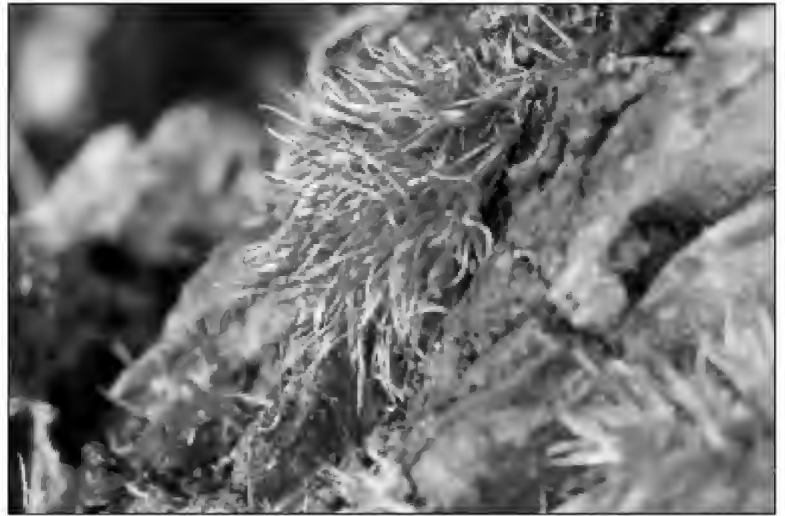


Fig. 1. *Brothera leana* growing on a rotting stump, 4× macro.

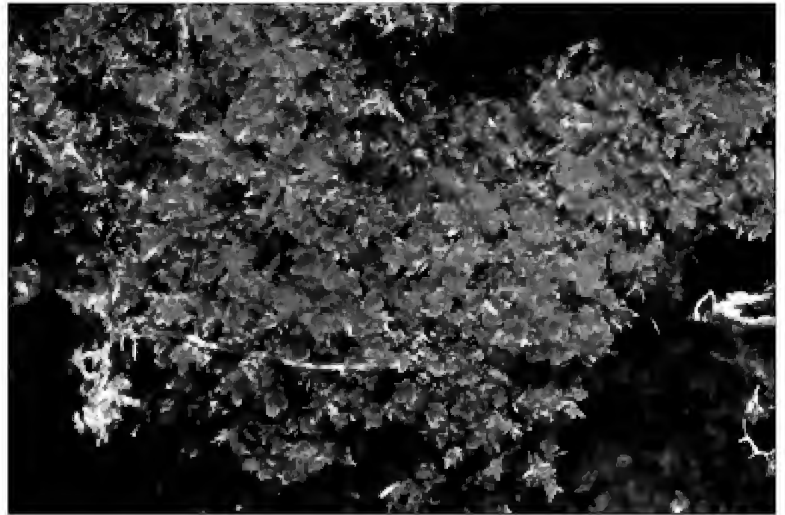


Fig. 2. *Crumia latifolia* growing on a rock emerging from the middle of a shallow creek, 1× macro.

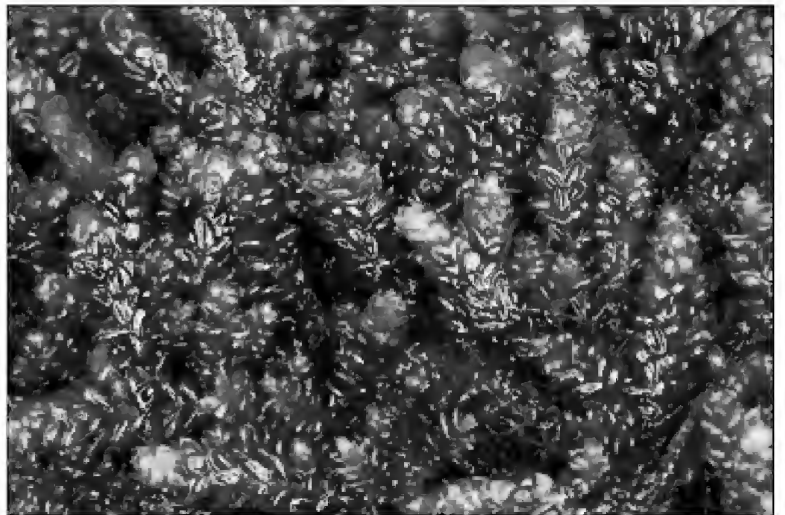


Fig. 3. *Entodon seductrix* growing on a cliff, 3× macro.

possible that this moss is simply uncommon and will eventually also be reported in states between New Mexico and the eastern populations.

Mannia californica (Gottsche ex Underw.) L.C. Wheeler is a new state record liverwort species. We also found a member of the liverwort genus *Fossombronia* in the Black Range, but it has yet to be found with sporophytes and cannot be identified with certainty to species. Our collection is the first member of the Fossombroniaceae to be reported in New Mexico. Further discussion of the liverworts can be found in the accompanying article by Blisard and Kleinman.

Conclusions

This ongoing study begins the process of documenting the bryophyte flora of the Gila National Forest in the literature. Work in the GNF has accelerated in recent years with the activity of Kelly Allred and now our own efforts. This study documents 116 moss species in 28 families and 18 liverwort species in 11 families from more than 500 collections during the past three years; four of the mosses and two of the liverworts are new state records.

Acknowledgments

We are grateful to the Gila National Forest and the National Park Service for granting us research permits. Steve Riley, park supervisor at the Gila Cliff Dwellings, was wonderfully supportive, as were the staff there. We also would like to thank those bryologists who consulted with us on particularly troublesome specimens: Bruce Allen, Roxanne Hastings, Paul Davison, and Brent Mishler. Richard Felger accompanied us on several of our field trips and provided assistance for which we are grateful.

We also acknowledge the support we have received from Western New Mexico University. This support has included not only assistance from the entire natural sciences department but also help from Steve Liebhart, who has given us space on the WNMU server to host the gilaflora.com website.

We are especially grateful to William R. Norris, professor of biology and curator of the Dale A. Zimmerman Herbarium at WNMU. Dr. Norris has helped us along every step of the way and has inaugurated the bryophyte section of the herbarium with specimens we have collected from the GNF.

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Table 1. Families of mosses found in the Gila National Forest.

Moss Family	Number of Species	Moss Family	Number of Species
Anomodontaceae	3	Funariaceae	1
Amblystegiaceae	8	Grimmiaceae	7
Aulacomniaceae	1	Hedwigiaceae	2
Bartramiaceae	3	Hypnaceae	9
Brachytheciaceae	12	Leskeaceae	5
Bryaceae	10	Meesiaceae	1
Climaciaceae	1	Mniaceae	6
Dicranaceae	6	Neckeraceae	1
Ditrichaceae	1	Orthotrichaceae	2
Encalyptaceae	2	Polytrichaceae	2
Entodontaceae	1	Pottiaceae	24
Fabroniaceae	1	Rhytidiaceae	1
Fissidentaceae	2	Thuidiaceae	1
Fontinalaceae	2	Timmiaceae	1

Table 2. Species of mosses found in the Gila National Forest.

Species	Family
<i>Amblystegium serpens</i> (Hedwig) Bruch & Schimper	Amblystegiaceae
<i>Anacolia laevisphaera</i> (Taylor) Flowers	Bartramiaceae
<i>Anomodon attenuatus</i> (Hedwig) Hübener	Anomodontaceae
<i>Anomodon minor</i> (Hedwig) Fürnrohr	Anomodontaceae
<i>Anomodon rostratus</i> (Hedwig) Schimper	Anomodontaceae
<i>Atrichum selwynii</i> Austin	Polytrichaceae
<i>Aulacomnium palustre</i> (Hedwig) Schwägrichen	Aulacomniaceae
<i>Barbula convoluta</i> Hedwig var. <i>convoluta</i>	Pottiaceae
<i>Barbula unguiculata</i> Hedwig	Pottiaceae
<i>Brachythecium acuminatum</i> (Hedwig) Austin	Brachytheciaceae
<i>Brachythecium albicans</i> (Hedwig) Schimper	Brachytheciaceae
<i>Brachythecium collinum</i> (Schleicher ex Müller Hal.) Schimper	Brachytheciaceae
<i>Brachythecium fendleri</i> (Sullivant) Jaeger	Brachytheciaceae
<i>Brachythecium laetum</i> (Bridel) Schimper in B.S.G.	Brachytheciaceae
<i>Brachythecium rivulare</i> Bruch & Schimper	Brachytheciaceae
<i>Brachythecium ruderales</i> (Bridel) W.R. Buck	Brachytheciaceae
<i>Brachythecium salebrosum</i> (Weber & Mohr) Bruch & Schimper	Brachytheciaceae
<i>Brachythecium velutinum</i> (Hedwig) Schimper	Brachytheciaceae
<i>Braunia secunda</i> (Hooker) Bruch, Schimper, & Gumbel	Hedwigiaceae
<i>Brothera leana</i> (Sullivant) Müller Hal.	Dicranaceae
<i>Bryoerythrophyllum recurvirostrum</i> (Hedwig) Chen	Pottiaceae
<i>Bryum argenteum</i> Hedwig	Bryaceae
<i>Bryum lanatum</i> (P. Beauvois) Bridel	Bryaceae
<i>Calliergonella lindbergii</i> (Mitten) Hedanäs	Hypnaceae
<i>Campyliadelphus chrysophyllus</i> (Bridel) Kanda	Amblystegiaceae
<i>Ceratodon purpureus</i> (Hedwig) Bridel	Ditrichaceae
<i>Climacium dendroides</i> (Hedwig) Weber & Mohr	Climaciaceae
<i>Conardia compacta</i> (Müller Hal.) Robinson	Amblystegiaceae
<i>Coscinodon calyptratus</i> (Hooker) C. Jensen ex Kindberg	Grimmiaceae
<i>Cratoneuron filicinum</i> (Hedwig) Spruce	Amblystegiaceae
<i>Crossidium squamiferum</i> (Viviani) Juratzka	Pottiaceae
<i>Crumia latifolia</i> (Kindberg) W. B. Schofield	Pottiaceae
<i>Dicranoweisia crispula</i> (Hedwig) Lindberg ex Milde	Dicranaceae
<i>Dicranum montanum</i> Hedwig	Dicranaceae
<i>Dicranum rhabdocarpum</i> Sullivant	Dicranaceae
<i>Dicranum scoparium</i> Hedwig	Dicranaceae
<i>Didymodon australasiae</i> (Greville & Hooker) Zander	Pottiaceae
<i>Didymodon rigidulus</i> Hedwig var. <i>rigidulus</i>	Pottiaceae
<i>Didymodon tophaceus</i> (Bridel) Lisa	Pottiaceae
<i>Didymodon vinealis</i> (Bridel) Zander	Pottiaceae
<i>Drepanocladus aduncus</i> (Hedwig) Warnstorf	Amblystegiaceae
<i>Encalypta ciliata</i> Hedwig	Encalyptaceae

Table 2 (cont'd)

Species	Family
<i>Encalypta vulgaris</i> Hedwig	Encalyptaceae
<i>Entodon seductrix</i> (Hedwig) Müller Hal.	Entodontaceae
<i>Eurhynchiastrum pulchellum</i> (Hedwig) Ignatov & Huttunen	Brachytheciaceae
<i>Fabronia ciliaris</i> (Bridel) Bridel	Fabroniaceae
<i>Fissidens bryoides</i> Hedwig	Fissidentaceae
<i>Fissidens crispus</i> Montagne	Fissidentaceae
<i>Fontinalis antipyretica</i> Hedwig	Fontinalaceae
<i>Fontinalis hypnoides</i> Hartman var. <i>hypnoides</i>	Fontinalaceae
<i>Funaria hygrometrica</i> Hedwig var. <i>hygrometrica</i>	Funariaceae
<i>Gemmabryum caespiticium</i> (Hedwig) J.R. Spence	Bryaceae
<i>Gemmabryum dichotomum</i> (Hedwig) Spence & Ramsay	Bryaceae
<i>Grimmia anodon</i> Bruch & Schimper	Grimmiaceae
<i>Grimmia laevigata</i> (Bridel) Bridel	Grimmiaceae
<i>Grimmia longirostris</i> Hooker	Grimmiaceae
<i>Grimmia ovalis</i> (Hedwig) Lindberg	Grimmiaceae
<i>Grimmia pulvinata</i> (Hedwig) Smith	Grimmiaceae
<i>Gymnostomum aeruginosum</i> Smith	Pottiaceae
<i>Haplocladium angustifolium</i> (Hampe & Müller Hal.) Brotherus	Leskeaceae
<i>Hedwigia ciliata</i> (Hedwig) P. Beauvois	Hedwigiaceae
<i>Homomallium mexicanum</i> Cardot	Hypnaceae
<i>Hygroamblystegium varium</i> (Hedwig) Mönkemeyer	Amblystegiaceae
<i>Hypnum cupressiforme</i> Hedwig var. <i>cupressiforme</i>	Hypnaceae
<i>Hypnum revolutum</i> (Mitten) Lindberg	Hypnaceae
<i>Hypnum vaucheri</i> Lesquereux	Hypnaceae
<i>Imbriobryum gemmiparum</i> (De Notaris) J.R. Spence	Bryaceae
<i>Imbriobryum miniatum</i> (Lesquereux) J.R. Spence	Bryaceae
<i>Leptobryum pyriforme</i> (Hedwig) Wilson	Meesiaceae
<i>Leptodontium flexifolium</i> (Withering) Hampe in Lindberg	Pottiaceae
<i>Leptodictum riparium</i> (Hedwig) Warnstorf	Amblystegiaceae
<i>Lindbergia brachyptera</i> (Mitten) Kindberg	Leskeaceae
<i>Mnium arizonicum</i> Amann	Mniaceae
<i>Molendoo sendtneriana</i> (Bruch & Schimper) Limpricht	Pottiaceae
<i>Neckera pennata</i> Hedwig	Neckeraceae
<i>Orthotrichum anomalum</i> Hedwig	Orthotrichaceae
<i>Orthotrichum diaphanum</i> Bridel	Orthotrichaceae
<i>Philonotis fontana</i> (Hedwig) Bridel	Bartramiaceae
<i>Philonotis marchica</i> (Hedwig) Bridel	Bartramiaceae
<i>Plagiobryoides incrassatolimata</i> (Cardot) J.R. Spence	Bryaceae
<i>Plagiomnium cuspidatum</i> (Hedwig) Koponen	Mniaceae
<i>Plagiomnium medium</i> (Bruch & Schimper) Koponen	Mniaceae
<i>Platydictya jungermannioides</i> (Bridel) Crum	Amblystegiaceae
<i>Platygyrium fuscoluteum</i> Cardot	Hypnaceae

Table 2 (cont'd)

Species	Family
<i>Pohlia cruda</i> (Hedwig) Lindberg	Mniaceae
<i>Pohlia nutans</i> (Hedwig) Lindberg	Mniaceae
<i>Polytrichum juniperinum</i> Hedwig	Polytrichaceae
<i>Pseudocrossidium crinitum</i> (Schultz) Zander	Pottiaceae
<i>Pseudocrossidium replicatum</i> (Taylor) Zander	Pottiaceae
<i>Pseudoleskea radicata</i> (Mitten) Macoun & Kindberg	Leskeaceae
<i>Pseudoleskeella arizonae</i> (Williams) E. Lawton	Leskeaceae
<i>Pseudoleskeella tectorum</i> (Funck ex Bridel) Kindberg	Leskeaceae
<i>Ptychostomum pseudotriquetrum</i> (Hedwig) J.R. Spence	Bryaceae
<i>Pylaisia polyantha</i> (Hedwig) Schimper	Hypnaceae
<i>Rhizomnium punctatum</i> (Hedwig) T. Koponen	Mniaceae
<i>Rhodobryum ontariense</i> (Kindberg) Kindberg	Bryaceae
<i>Rhynchostegium riparioides</i> (Hedwig) Cardot	Brachytheciaceae
<i>Rhynchostegium serrulatum</i> (Hedwig) Jaeger & Sauerbeck	Brachytheciaceae
<i>Rhytidium rugosum</i> (Hedwig) Kindberg	Rhytidiaceae
<i>Rosulabryum laevifilum</i> (Syed) Ochyra	Bryaceae
<i>Sanionia uncinata</i> (Hedwig) Loeske	Amblystegiaceae
<i>Schistidium rivulare</i> (Bridel) Podpera	Grimmiaceae
<i>Symblepharis vaginata</i> (Hooker) Wijk & Margadant	Dicranaceae
<i>Syntrichia bartramii</i> (Steere) Zander	Pottiaceae
<i>Syntrichia fragilis</i> (Taylor) Ochyra	Pottiaceae
<i>Syntrichia laevipila</i> Bridel	Pottiaceae
<i>Syntrichia ruralis</i> (Hedwig) Weber & Mohr	Pottiaceae
<i>Taxiphyllum deplanatum</i> (Bruch & Schimper ex Sullivant) Fleischer	Hypnaceae
<i>Thuidium delicatulum</i> (Hedwig) Bruch & Schimper	Thuidaceae
<i>Timmia megapolitana</i> Hedwig var. <i>bavarica</i> (Hessler) Bridel	Timmiaceae
<i>Tortella tortuosa</i> (Hedwig) Limpricht	Pottiaceae
<i>Tortula inermis</i> (Bridel) Montagne	Pottiaceae
<i>Tortula</i> cf. <i>plinthobia/muralis</i>	Pottiaceae
<i>Trichostomum tenuirostre</i> (Hooker & Taylor) Lindberg	Pottiaceae
<i>Weissia controversa</i> Hedwig	Pottiaceae
<i>Weissia ligulifolia</i> (Bartram) Grout	Pottiaceae

Table 3. Liverwort species found in the Gila National Forest.

Liverwort Species	Family
<i>Barbilophozia barbata</i> (Schmid. ex Schreb.) Loeske	Jungermanniaceae
<i>Cephaloziella hampeana</i> (Nees) Schiffn. ex Loeske	Cephaloziellaceae
<i>Chiloscyphus polyanthos</i> (Linnaeus) Corda	Geocalycaceae
<i>Fossombronia</i> sp.	Fossombroniaceae
<i>Frullania inflata</i> Gottsche	Jubulaceae
<i>Frullania riparia</i> Hampe ex Lehm.	Jubulaceae
<i>Jungermannia exsertifolia</i> Steph. subsp. <i>cordifolia</i> (Dumort.) Váša	Jungermanniaceae
<i>Jungermannia leiantha</i> Grolle	Jungermanniaceae
<i>Lepidozia reptans</i> (Linnaeus) Dumort.	Lepidoziaceae
<i>Lophozia ventricosa</i> (Dicks.) Dum.	Jungermanniaceae
<i>Mannia californica</i> (Gottsche ex Underw.) L.C. Wheeler	Aytoniaceae
<i>Mannia fragrans</i> (Balb.) Frye & L. Clark	Aytoniaceae
<i>Marchantia polymorpha</i> Linnaeus subsp. <i>polymorpha</i>	Marchantiaceae
<i>Marchantia polymorpha</i> Linnaeus subsp. <i>montivagans</i> Bischn. & Boissel.-Dub.	Marchantiaceae
<i>Plagiochasma wrightii</i> Sullivant	Aytoniaceae
<i>Plagiochila asplenoides</i> (Linnaeus) Dumort.	Plagiochilaceae
<i>Porella platyphylla</i> (Linnaeus) Pfeiff.	Porellaceae
<i>Radula complanata</i> (Linnaeus) Dumort.	Radulaceae
<i>Reboulia hemisphaerica</i> (Linnaeus) Raddi	Aytoniaceae

Late Cenozoic Vertebrate Faunas from the Gila Region of Southwestern New Mexico

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Abstract

Late Cenozoic vertebrate fossils from the Gila Region in southwestern New Mexico document dramatic changes in this fauna over the past 6 million years. These fossils are from localities west of the Continental Divide within the valley of the modern Gila River and its tributaries in Catron, Grant, and Hidalgo counties. Sediments of the Gila Group near Glenwood in southern Catron County have produced several late Miocene mammals, including the rhinoceros *Teleoceras fossiger* and the three-toed horse *Neohipparion eurystyle*. The latest Miocene Walnut Canyon Fauna, from Gila Group strata southeast of Gila in northern Grant County, consists of 12 species of mammals, including several species typical of the late Hemphillian North American land mammal age (NALMA): the fox *Cerdocyon texanus*, the horses *Astrohippus stockii* and *Dinohippus mexicanus*, and the deer *Eocoileus gentryorum*. The early Pliocene Buckhorn Fauna, derived from lacustrine sediments of the Gila Group northwest of Buckhorn in northern Grant County, has about 25 species of vertebrates, several of which are diagnostic of the Blancan NALMA, including the dwarf three-toed horse *Nannippus peninsulatus*, the one-toed horse *Equus simplicidens*, the primitive coyote *Canis lepophagus*, and the rodent *Ogmodontomys poaphagus*. Two other Blancan faunas, the latest Pliocene Pearson Mesa and earliest Pleistocene Virden faunas, occur in the Gila River Valley along the New Mexico/Arizona border in northern Hidalgo County. Pearson Mesa has five horses, *Nannippus* and four species of *Equus*, and the ground sloth *Paramylodon garbanii*, a late Pliocene participant in the Great American Biotic Interchange. The slightly younger Virden Fauna has a second Interchange species, the glyptodont *Glyptotherium arizonae*, and also contains the latest Blancan llama *Hemiauchenia gracilis*. The late Pleistocene (Rancholabrean NALMA) Canovas Creek Fauna, located southwest of Quemado in northern Catron County, is one of the highest-elevation (2,375 m) Pleistocene sites in New Mexico. Canovas Creek has 17 species of vertebrates, including five extinct mammals, the horses *Equus conversidens* and *E. occidentalis*, the giant llama *Camelops hesternus*, the pronghorn cf. *Stockoceros* sp., and the Columbian mammoth *Mammuthus columbi*.

Introduction

The Gila Region encompasses a vast expanse of southwestern New Mexico in Catron, Grant, Sierra, and Hidalgo counties.

It is a mountainous area composed mostly of Cenozoic volcanic rocks dissected by two major rivers, the Gila River and San Francisco River. Two major mountain ranges are found in the Gila, the Mogollon Mountains in Catron and Grant counties and the Black Range in Sierra County, together with several smaller ranges including the Big Burro Mountains and Tularosa Mountains. The Continental Divide bisects the region, with the Black Range and the Rio Grande watershed on the eastern side and the Mogollon Mountains and Gila River watershed on the western side. Miocene and Pliocene sedimentary rocks of the Gila Group found along the valleys and tributaries of the Gila and San Francisco rivers have produced most of the Late Cenozoic fossil sites in the Gila Region. All of the Late Cenozoic fossil sites described here are from west of the Continental Divide in Catron, Grant, and Hidalgo counties (Fig. 1).

Late Cenozoic vertebrates have been known from the Gila Region since the late 19th century, beginning with the well-known paleontologist Edward Drinker Cope (1884), who reported a partial skull of the Miocene rhinoceros "*Aphelops*" (now *Teleoceras*) *fossiger* from Big Dry Creek near its junction with the San Francisco River in southern Catron County. After a hiatus of nearly 70 years, vertebrate paleontological field work in the Gila Region resumed in 1953 when George Pearce of the Frick Laboratory at the American Museum of Natural History (AMNH) collected a Pliocene fauna near Buckhorn in northern Grant County. Pearce's collection was briefly summarized by Leopoldt (1981) and Tedford (1981). A few late Miocene horse teeth were collected in the 1970s near Gila in northern Grant County (Tedford 1981). Paul Sealey of the New Mexico Museum of Natural History (NMMNH) prospected for fossils in Gila Group outcrops near Buckhorn and Gila in the late 1980s and early 1990s, leading to the discovery of Pliocene fossils on the McKeen Ranch in the vicinity of Duck Creek near Buckhorn and Miocene fossils on the Brown Ranch along the North Fork of Walnut Canyon southeast of Gila. In the mid to late 1990s, Sealey, Gary Morgan, and NMMNH crews continued field work in this area, including the excavation of Miocene fossils from the Walnut Canyon Horse Quarry on the Brown Ranch and the discovery of additional Pliocene sites on the McKeen Ranch, resulting in the description of the late Miocene Walnut Canyon and early Pliocene Buckhorn vertebrate faunas (Morgan et al. 1997). In a paper on Pliocene small mammals from Gila Group sediments in the Duncan basin in southeastern Arizona, Tomida (1987) mentioned several fossils

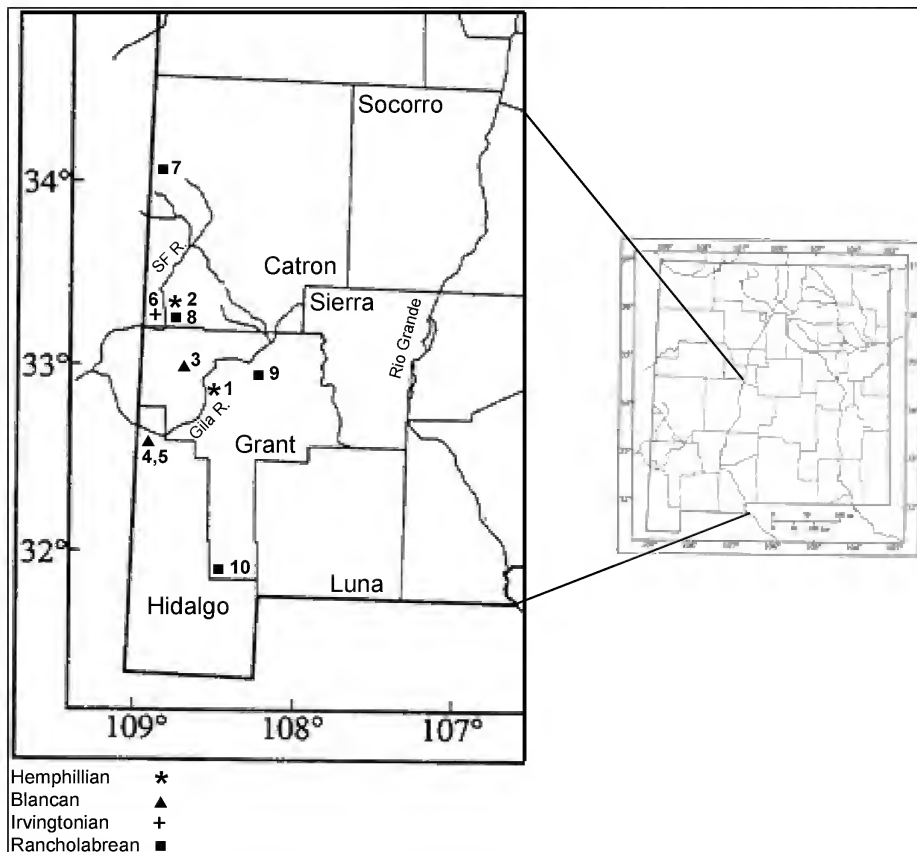


Fig. 1. Map of the Gila Region in southwestern New Mexico showing the location of the principal Cenozoic vertebrate fossil sites discussed in the text. Miocene (Hemphillian NALMA, designated by asterisk): 1. Walnut Canyon, Grant County; 2. Glenwood, Catron County. Pliocene (Blancan NALMA, designated by triangle): 3. Buckhorn, Grant County; 4. Pearson Mesa, Hidalgo County; 5. Virden, Hidalgo County. Pleistocene (Irvingtonian NALMA, designated by plus sign): 6. San Francisco River, Catron County. (Rancholabrean NALMA, designated by square): 7. Canovas Creek, Catron County; 8. Shelton Canyon, Catron County; 9. Sapillo Creek, Grant County; 10. Howell's Ridge Cave, Grant County. SF R. is the San Francisco River.

from Pearson Mesa on the New Mexico/Arizona border. Field work on Pearson Mesa by Morgan, Sealey, and NMMNH crews from 1998 to 2012 led to the discovery of two vertebrate faunas, the late Pliocene Pearson Mesa Fauna and the earliest Pleistocene Virden Fauna (Morgan et al. 2008). The most recent fossil find in the Gila Region is the late Pleistocene Canovas Creek Local Fauna, discovered by Chris Wonderly in 2010 in northwestern Catron County.

This paper reviews the most important Late Cenozoic vertebrate faunas from the Gila Region, including the late Miocene Walnut Canyon Fauna, the early Pliocene Buckhorn Fauna, the late Pliocene Pearson Mesa Fauna, the early Pleistocene Virden Fauna, and the late Pleistocene Canovas Creek Fauna. This is the first report of fossils from the Canovas Creek site.

Methods and Materials

Site descriptions, field photos, historical and faunal reviews, faunal lists, specimen photos, and pertinent references are

provided for the major Late Cenozoic vertebrate faunas from the Gila Region. Each of the major sites consists of large samples of fossil specimens representing from 14 to nearly 30 species. Brief information is presented for several lesser-known sites, primarily from the literature.

Most of the fossils described in this paper are housed in the vertebrate paleontology collection of the New Mexico Museum of Natural History and Science, Albuquerque, New Mexico (NMMNH). Several smaller fossil samples are in the Frick Collection (F:AM; Frick American Mammals) at the American Museum of Natural History in New York (AMNH) and in the collection of the US Geological Survey in Denver (USGSD). Other abbreviations used in this paper are the following: thousands of years (ka), millions of years (Ma), Local Fauna (LF), New Mexico Bureau of Geology and Mineral Resources (NMB-GMR), North American land mammal age (NALMA), Great American Biotic Interchange (GABI), New Mexico Friends of Paleontology (NMFOP), US Bureau of Land Management (BLM), US Forest Service (USFS). The abbreviations for tooth positions are standard for mammals, with uppercase letters for upper teeth and lowercase letters for lower teeth: I/i (upper/lower incisor), C/c (upper/lower canine), P/p (upper/lower premolar), and M/m (upper/lower molar). For example, P4 is an upper fourth premolar and m3 is a lower third molar.

Chronology

This paper reviews Late Cenozoic (= Neogene) vertebrate faunas from the Gila Region, covering the time period from the latest Miocene (about 6 Ma) to the late Pleistocene (about 10 ka). Fossils are reported from three epochs, the Miocene, Pliocene, and Pleistocene. The officially recognized boundaries between these epochs are as follows: the Miocene/Pliocene boundary is 5.3 Ma, the Pliocene/Pleistocene boundary is 2.6 Ma, and the Pleistocene/Holocene boundary is 10 ka (Gradstein et al. 2004; Gibbard et al. 2010). Besides the more familiar epochs, the Cenozoic Era in North America also has been subdivided into segments of time of about 3 to 5 million years in duration called the North American land mammal ages (NALMA), characterized by unique faunas of mammals generally at the genus level (Bell et al. 2004; Tedford et al. 2004). Faunas diagnostic of three, and possibly four, NALMA are recognized in the Gila Region (epochs and

time ranges for the NALMA in parentheses): Hemphillian NALMA (late Miocene and earliest Pliocene; 9.0–4.9 Ma); Blancan NALMA (early Pliocene, late Pliocene, and earliest Pleistocene; 4.9–1.6 Ma); Irvingtonian NALMA (early and medial Pleistocene; 1.6–0.25 Ma); and Rancholabrean NALMA (late Pleistocene; 250–10 ka). Among these four NALMA, Hemphillian, Blancan, and Rancholabrean faunas are definitely present in the Gila Region, whereas one fauna could be either Irvingtonian or Rancholabrean. The ages and characterizing mammalian faunas for these NALMAs follow Tedford et al. (2004) for the Hemphillian NALMA and Bell et al. (2004) for the Blancan, Irvingtonian, and Rancholabrean NALMAs. Subdivisions of these NALMAs help to further delimit smaller intervals of time. Subdivisions of the Hemphillian and Blancan NALMAs used here are (epoch and age range in Ma in parentheses) early late Hemphillian (late Miocene; 7.0–5.9 Ma); latest Hemphillian (latest Miocene/earliest Pliocene; 5.9–4.9 Ma); earliest Blancan (early Pliocene; 4.9–4.0 Ma); late early Blancan (late early and early late Pliocene; 4.0–3.0 Ma); early late Blancan (latest Pliocene and earliest Pleistocene; 3.0–2.2 Ma); latest Blancan (early Pleistocene, 2.2–1.6 Ma). There are also subdivisions of the Irvingtonian and Rancholabrean, but these cannot be distinguished in faunas from the Gila Region.

Geologic Setting

The Gila Region has a complex geologic history relating to its location between two well-known physiographic provinces, the Colorado Plateau on the north and the Basin and Range on the south and east. Most of the Gila is recognized as a separate physiographic province, the Datil-Mogollon section of the Transition Zone (Hawley 2005). The westernmost portion of the Gila River in New Mexico where it crosses the border into Arizona is located in the Basin and Range Province (Hawley 2005; Summer 2012). Mountains composed of Eocene and Oligocene volcanic rocks dominate the landscape over much of the Gila Region (Chapin et al. 2004). There are also several structural basins at lower elevations west of the Continental Divide that contain Cenozoic sedimentary rocks (Mack 2004; Mack and Stout 2005). Miocene and Pliocene sediments of the Gila Group (also called the Gila Conglomerate or Gila Formation) in the Mangas and Duncan basins have produced Late Cenozoic vertebrate faunas (Morgan et al. 1997, 2008). The Mangas basin is located in southern Catron County and northern Grant County. The Duncan basin is farther south and west, along the New Mexico/Arizona border in Hidalgo County, New Mexico, and Greenlee County, Arizona.

The Mangas basin (also called the Mangas graben or Mangas trench) is an extensional basin trending from northwest to southeast for about 100 km, between the Mogollon Rim and the Colorado Plateau on the north and the Basin and Range on the south and Rio Grande rift to the east (Mack and Stout 2005). The basin is surrounded by uplifted mountain ranges, bordered on the east by the Mogollon Mountains and on the west by a series of smaller

ranges. Two major rivers transect the Mangas basin from east to west, the San Francisco River in the northern half of the basin and the Gila River in the central and southern part of the basin, both of which flow into southeastern Arizona. The Mangas basin contains a maximum thickness of about 200 m of upper Miocene and Pliocene sedimentary rocks of the Gila Group that overlie the Harve Gulch basalt dated at 5.6 ± 0.3 Ma (Ratté and Finnell 1978; Houser 1987). Mack and Stout (2005) recognized three facies of Gila Group strata within the Mangas basin, axial-fluvial, axial-fan, and lacustrine, each of which has produced vertebrate fossils. Latest Miocene (latest Hemphillian NALMA) faunas are derived from indurated conglomerates of the axial-fluvial facies near Glenwood in southern Catron County (Glenwood Fauna) and finer-grained sediments of the axial-fan facies southeast of Cliff and Gila along the North Fork of Walnut Canyon (Walnut Canyon Fauna). The youngest vertebrate fauna in the Mangas basin, the early Pliocene (early Blancan NALMA) Buckhorn LF, occurs in the lacustrine facies (Morgan et al. 1997; Mack and Stout 2005). Mudstones and other fine-grained sediments (e.g., diatomites) of the lacustrine facies were deposited either within or along the shore of a Pliocene and early Pleistocene lake named Lake Buckhorn (Mack and Stout 2005).

Strata of the upper Gila Group are exposed along the northwestern, western, and southwestern margins of Pearson Mesa, south of the village of Virden and south of the Gila River in Hidalgo County, New Mexico, and extending westward barely a mile into Greenlee County in southeastern Arizona. These strata consist of about 100 m of unconsolidated gravels, sandstones, and mudstones, informally termed the “Pearson Mesa Member” of the Gila Formation or Gila Group, and interpreted as alluvial-fan or alluvial-flat deposits (Mack 2004). Pearson Mesa is located in the eastern portion of the Duncan basin (Virden basin in Mack 2004), formed by Basin and Range extensional tectonics (Hawley 2005; Summer 2012). Gila Group sediments on Pearson Mesa have produced two diverse vertebrate faunas, the late Pliocene (late Blancan) Pearson Mesa LF and the slightly younger early Pleistocene (latest Blancan) Virden LF (Morgan et al. 2008). Somewhat older early Pliocene (early Blancan) vertebrate fossils referred to the Duncan Fauna are known from lower in the Gila Group section in the western portion of the Duncan basin near the town of Duncan in Greenlee County (Tomida 1987).

Late Miocene Vertebrate Faunas (Latest Hemphillian NALMA)

Walnut Canyon

The Walnut Canyon Local Fauna (LF) includes one major locality, the Walnut Canyon Horse Quarry, and several smaller sites located along the North Fork of Walnut Canyon, about 6 km east of the Gila River, 5 km southeast of the town of Gila, and just north of Table Butte, northern Grant County (Figs. 1, 2). These sites occur over an area of less than 1 square kilometer and within a stratigraphic interval of less than 10 m

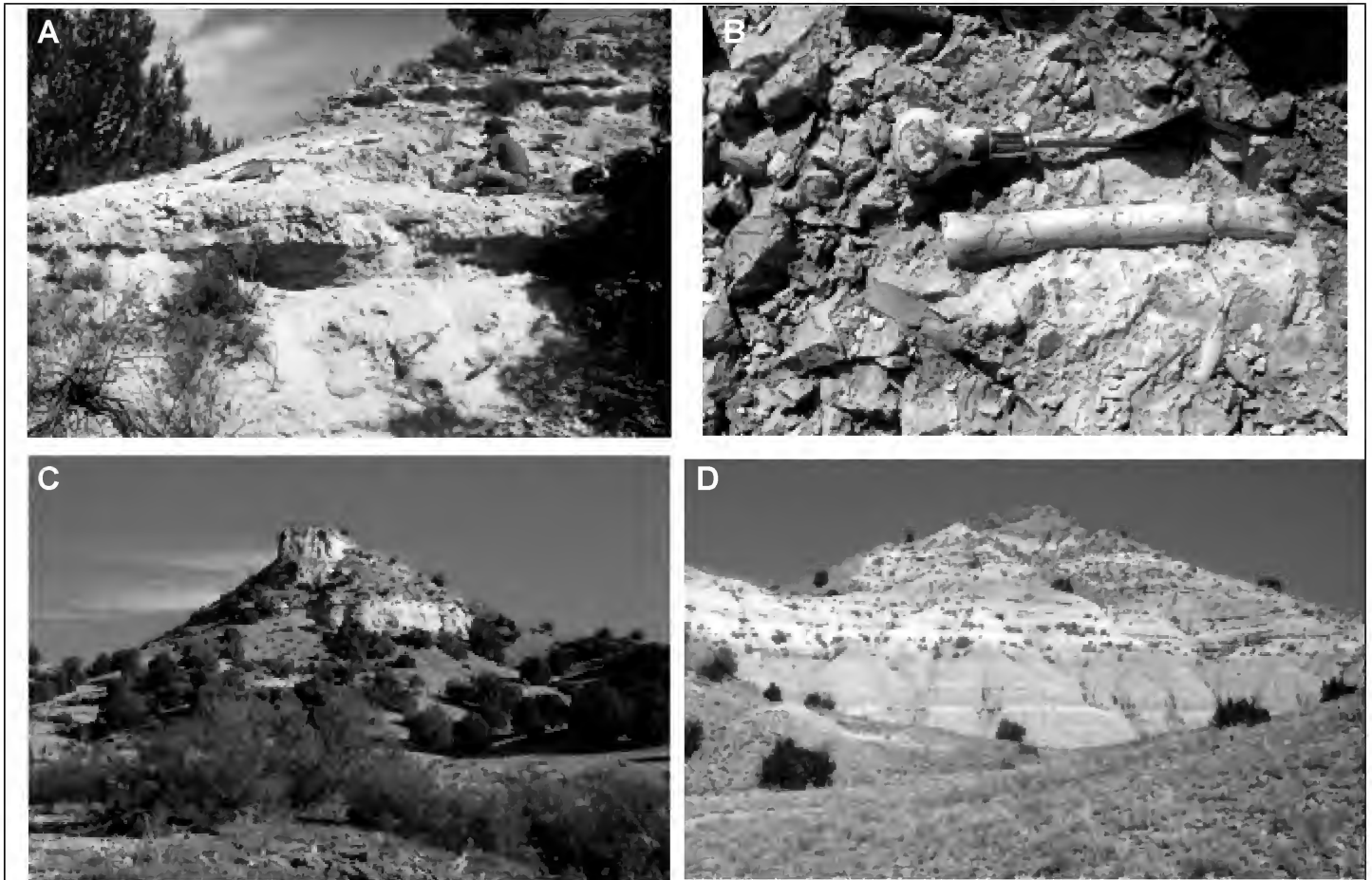


Fig. 2. Photographs of Gila Group outcrops in the Mangas basin, Grant County, New Mexico. A. Paleontologist excavating fossils in the Walnut Canyon Horse Quarry, which produced a rich late Miocene (late Hemphillian) vertebrate fauna. B. Close-up view of a metacarpal of the small horse *Astrohippus stockii* in place in the Walnut Canyon Horse Quarry, awl for scale (see

photo of this same bone in Fig. 3D). C. Gila Group rocks on Table Butte, about 2 km south of the Walnut Canyon Horse Quarry. D. Gila Group outcrops near Buckhorn, in the vicinity of where the early Pliocene (early Blancan) Buckhorn Local Fauna was collected.

in light-colored mudstones of the axial-fan facies of the upper Gila Group (Morgan et al. 1997; Mack and Stout 2005). Most of the key sites are located on the ranch of Wesley and Lillian Brown, who first found vertebrate fossils along the North Fork of Walnut Canyon in the 1970s (Leopoldt 1981). William Strain of the University of Texas at El Paso identified two horse teeth from Walnut Canyon as *Pliohippus* (Cunningham 1974). At that time, species now placed in the genera *Astrohippus* and *Dinohippus* commonly were referred to *Pliohippus*. Tedford (1981) mentioned the late Hemphillian horses *Astrohippus stockii* and *Dinohippus* from the Walnut Canyon locality and Leopoldt (1981) listed these two horses, as well as a tayassuid, two camelids, and a rabbit.

Paul Sealey of the NMMNH discovered the Walnut Canyon Horse Quarry (NMMNH locality L-2922) in 1989, and also collected fossils from several additional sites about 0.5 km farther south, between the Horse Quarry and Table Butte. One of those sites (NMMNH locality L-2926) yielded a mandible of the fox *Cerdocyon* and an upper molar of the deer *Eocoileus*, two mammals not identified from the Horse Quarry. Excavation of the Walnut Canyon Horse

Quarry between 1994 and 1997 by Sealey, Gary Morgan, and NMMNH crews produced most of the fossils from the Walnut Canyon LF (Morgan et al. 1997; Table 1). There is no articulation of elements in the Horse Quarry and only a few associated dentitions, mostly of the small horse *Astrohippus stockii* but also including several associated lower teeth of the larger horse *Dinohippus* and a skull fragment with three teeth of a medium-sized antilocaprid. Most other fossils in the quarry consist of isolated teeth and postcranial elements, as well as numerous broken, unidentifiable bone fragments. Fossils of small mammals are uncommon and include two teeth of lagomorphs, a rodent calcaneum, and several postcranial elements of small carnivores, most of which were collected during excavation. Very few microvertebrate fossils were recovered from screenwashing. No fossils of fish, amphibians, reptiles, or birds were found in the Walnut Canyon Horse Quarry.

The Walnut Canyon LF is composed of 14 species of mammals, including 2 lagomorphs, 1 rodent, 3 carnivores, 2 horses, 1 peccary, 3 camels, 1 deer, and 1 pronghorn (Table 1). Typical mammalian fossils from the Walnut Canyon LF

are illustrated in Figure 3. The most common species in the Walnut Canyon Horse Quarry is the small horse *Astrohippus stockii*, including at least five individuals constituting more than half of all identifiable fossils from this site. Next in abundance are the larger horse *Dinohippus mexicanus* and the camel *Pleiolama* cf. *P. vera*, represented by several individuals each. *Astrohippus* and *Dinohippus* are both advanced one-toed or monodactyl horses, with each limb supported by the 3rd digit, composed of the 3rd metacarpal/metatarsal and the associated proximal, medial, and ungual phalanges. *Astrohippus stockii* is the last known species in this genus and became extinct at the end of the Hemphillian. *D. mexicanus* or a similar species gave rise to the one-toed horse genus *Equus* in the early Pliocene (early Blancan NALMA). The Walnut Canyon LF is the only site in New Mexico with *A. stockii* and *D. mexicanus*, originally described from the latest Hemphillian Yepómera LF from Chihuahua in northern Mexico (Lance 1950; MacFadden 1984a).

Three camels are present in the Walnut Canyon LF, representing small, medium, and large species, referred to the genera *Pleiolama*, *Alforjas*, and *Megatylopus*, respectively. These three genera of camelids are typically found in late Hemphillian faunas in western North America (Harrison 1979). A lamine camel with slender, elongated limbs is tentatively referred to the late Hemphillian species *Pleiolama vera*, previously referred to the genus *Hemiauchenia* (Morgan et al. 1997). Webb and Meachen (2004) described *Pleiolama*, the earliest genus of llama-like camels (tribe Lamini), based on several species from the late Miocene, including *P. vera*. The two larger camels are represented primarily by postcranial elements, here tentatively referred to the large lamine *Alforjas* and the giant camel *Megatylopus*. A low-crowned upper molar of a ruminant artiodactyl from the Walnut Canyon LF, originally identified as an unknown cervid (Morgan et al. 1997), is very similar to the extinct genus and species *Eocoileus gentryorum*, the earliest deer from the New World, described from the latest Hemphillian Palmetto Fauna in Florida (Webb 2000). A lower second premolar (p2) and an upper third molar (M3) of a peccary from the Walnut Canyon LF were tentatively referred to extinct late Hemphillian tayassuid species *Catagonus brachydontus* (Morgan et al. 1997). This peccary was described from the Ocote LF in central Mexico (Dalquest and Mooser 1980) and later identified from the Palmetto Fauna in Florida (Wright 1989), both latest Hemphillian in age.

The only carnivore from the Walnut Canyon LF represented by diagnostic cranial material is a mandible with a first lower molar (m1) of the small fox-like canid *Cerdocyon texanus*, first described from a latest Hemphillian fauna in the Texas Panhandle (Tedford et al. 2009). This jaw was referred to the small fox *Vulpes stenognathus* by Morgan et al. (1997), but was later reidentified as *Cerdocyon texanus* (Tedford et al. 2009). A toe tentatively identified as the small tremarctine bear *Plionarctos* was collected from the Walnut Canyon Horse Quarry in 2005 and thus was not included on the original mammalian fauna list from that site (Morgan et al. 1997). Most other ursids from late Hemphillian faunas belong to

Table 1. Latest Miocene (latest Hemphillian) mammals from the Gila Group, Mangas basin, southwestern New Mexico. Taxa followed by the superscript “G” are from the Glenwood Fauna of southern Catron County. The remaining taxa comprise the Walnut Canyon Local Fauna from several localities along the North Fork of Walnut Canyon southeast of Gila in northern Grant County. Genera are listed alphabetically within a family. Taxa that lack adequate material for a more precise identification are listed as indet. (indeterminate). The symbol † designates an extinct species.

Carnivora	
Canidae	† <i>Cerdocyon texanus</i> ¹
Ursidae	cf. <i>Plionarctos</i> sp.
Felidae	genus and species indet.
Lagomorpha	
Leporidae	genus and species indet.—large ^{2, G}
	genus and species indet.—small
Rodentia	
	family, genus, and species indet.
Perissodactyla	
Equidae	† <i>Astrohippus stockii</i>
	† <i>Dinohippus mexicanus</i>
	† <i>Neohipparion eurystyle</i> ^G
Rhinocerotidae	† <i>Teleoceras fossiger</i> ^G
Artiodactyla	
Tayassuidae	† <i>Catagonus</i> cf. <i>C. brachydontus</i>
Camelidae	cf. <i>Alforjas</i> sp.
	<i>Megatylopus</i> sp.
	† <i>Pleiolama</i> cf. <i>P. vera</i>
Antilocapridae	genus and species indet.
Cervidae	† <i>Eocoileus</i> cf. <i>E. gentryorum</i> ³
Proboscidea	
Gomphotheriidae	cf. <i>Rhynchotherium</i> sp. ^G

1. Identified as *Vulpes stenognathus* by Morgan et al. (1997); referred to *Cerdocyon texanus* by Tedford et al. (2009).
2. A large unidentified genus and species of rabbit (Lagomorpha) is known from both the Walnut Canyon Local Fauna and the Glenwood Fauna. A smaller rabbit is known only from Walnut Canyon.
3. Identified as “Cervidae genus and species indeterminate” by Morgan et al. (1997). Very similar to *Eocoileus gentryorum*, described subsequently from the latest Hemphillian Palmetto Fauna in Florida (Webb 2000).



Fig. 3. Photographs of mammalian fossils from the latest Miocene (latest Hemphillian NALMA) Walnut Canyon Fauna (A–L), Grant County, and Glenwood Fauna (M–N), Catron County, New Mexico. A. *Astrohippus stockii*, occlusal view of associated left P2-P3 (NMMNH 37524). B. *Astrohippus stockii*, occlusal view of associated right M2-M3 (NMMNH 26745). C. *Astrohippus stockii*, occlusal view of associated left p4-m1 (NMMNH 26751). D. *Astrohippus stockii*, metacarpal 3 (NMMNH 26756). E. Proximal phalanges of *Astrohippus stockii* (left, NMMNH 26768) and *Dinohippus mexicanus* (right, NMMNH 26798). F. *Dinohippus mexicanus*,

occlusal view of right p2 (NMMNH 26789). G. *Dinohippus mexicanus*, occlusal view of left p4 (NMMNH 26788). H. *Dinohippus mexicanus*, occlusal view of left m2 (NMMNH 26788). I. *Eocoileus* cf. *E. gentryorum*, occlusal view of left M3 (NMMNH 26859). J. *Cerdocyon texanus*, lateral view of right mandible with m1 (NMMNH 26861). K. Ursidae, cf. *Plionarctos* sp., medial phalanx (NMMNH 63858). L. *Catagonus* cf. *C. brachydontus*, lateral view of right p2 (NMMNH 26837). M. Medial view and N. occlusal view, *Neohipparion eurystyle*, left m2 (NMMNH 31597). Each of the blue-and-white squares on the scales is 1 cm in width.

the genus *Agriotherium*, which is nearly twice as large as the Walnut Canyon bear.

The small canid *Cerdocyon texanus*, the equids *Astrohippus stockii* and *Dinohippus mexicanus*, the tayassuid *Catagonus brachydontus*, and the cervid *Eocoileus gentryorum* are all indicative of latest Hemphillian faunas (MacFadden 1984a; Wright 1989; Webb 2000; Tedford et al 2009). Latest Hemphillian faunas span the Miocene/Pliocene boundary (5.3 Ma), ranging in age from latest Miocene (5.9–5.3 Ma) to earliest Pliocene (5.3–4.9 Ma; Tedford et al. 2004). The Walnut Canyon Horse Quarry is latest Hemphillian based on the mammalian biochronology, but it cannot yet be determined whether the fauna is latest Miocene or earliest Pliocene in age. The age of the Walnut Canyon LF is restricted to between 5.6 and 4.9 Ma, based on a latest Miocene date of 5.6 Ma on the Harve Gulch basalt that underlies that strata containing the Walnut Canyon LF, the presence of mammals indicative of the latest Hemphillian NALMA, and the occurrence of the early Blancan Buckhorn Fauna in overlying sediments of the upper Gila Group in the Mangas basin. The Walnut Canyon LF correlates with several other latest Hemphillian faunas from the southern United States and Mexico, including Christian Ranch from the Texas Panhandle (Schultz 1977), Yepómera from northern Mexico (Lance 1950; MacFadden 1984a), Ocote from central Mexico (Dalquest and Mooser 1980), and Palmetto from Florida (Webb et al. 2008).

From a biogeographic perspective, it is interesting that a number of mammals from the Walnut Canyon LF appear to have affinities with species that emigrated to South America in the Pliocene or early Pleistocene as participants in the Great American Biotic Interchange (GABI). The extinct fox *Cerdocyon texanus* from Walnut Canyon belongs to the same genus as the living crab-eating fox *Cerdocyon thous* from tropical South America. *Cerdocyon* evolved in North America in the late Miocene and then dispersed to South America in the Plio-Pleistocene during the GABI. Similarly, the extinct late Hemphillian peccary *Catagonus brachydontus* belongs to the same genus as the extant Chacoan peccary *Catagonus wagneri* from southern South America. *Catagonus* originated in North America and then dispersed to South America as a participant in the Interchange. Three other extinct genera from Walnut Canyon also have affinities with mammals that participated in the Interchange, the deer *Eocoileus*, the llama *Pleiolama*, and the bear *Plionarctos*. Webb (2000) suggested that the extinct cervid genus *Eocoileus* was closely related to two genera of South American deer, *Mazama* and *Ozotoceros*. The early llama *Pleiolama* is a precursor of the long-limbed llama *Hemiauchenia*, an extinct genus that evolved in North America and dispersed to South America as a participant in the GABI. The small tremarctine bear *Plionarctos* probably gave rise in the Pliocene to *Tremarctos*, which migrated to South America during the Interchange and survives today as *Tremarctos ornatus*, the Andean spectacled bear. It would appear that the latest Miocene/earliest Pliocene time frame and the geographic location of Walnut Canyon in the southwestern United States were both factors that led to several taxa of mammals from this fauna, or their closely related descen-

dants, being involved in the Interchange with South America in the Pliocene and early Pleistocene.

Glenwood

Several localities of late Miocene (late Hemphillian) age are known from strata of the Gila Group near Glenwood in southern Catron County, in the northern part of the Mangas basin (Fig. 1). Table 1 lists four mammals from the vicinity of Glenwood, here named the Glenwood Fauna: the rhinoceros *Teleoceras fossiger*; the three-toed horse *Neohipparion eurystyle*; a mastodon or gomphothere, probably the genus *Rhynchotherium*; and an unidentified rabbit. The first three of these species are not present in the Walnut Canyon LF, whereas rabbits are known from both Glenwood and Walnut Canyon. The fossils from the Glenwood area were collected from indurated conglomeratic sediments typical of the Gila Conglomerate, now recognized as belonging to the Gila Group (Morgan et al. 1997). According to Mack and Stout (2005), Gila Group strata in the northern part of the Mangas basin, including the conglomeratic sediments from the Glenwood area, represent fluvial-channel deposits of a south-flowing river.

Edward Drinker Cope (1884, p. 59) identified “the skull of a species of rhinoceros of the typical Loup Fork genus *Aphelops*. It is apparently the *A. fossiger* Cope, a species abundant in the Loup Fork beds of Kansas and Nebraska.” The species *fossiger* has since been transferred to *Teleoceras*, a genus of robust, short-legged rhinos, thought to have been semi-aquatic, possibly the ecological equivalent of a hippo. *Teleoceras fossiger* is typical of late Miocene (Hemphillian faunas). Cope (1884) noted that the rhino skull was found by a Mr. Robert Seip in a conglomerate bed near the mouth of Big Dry Creek (where it enters the San Francisco River), about 6 miles southwest of Glenwood in southernmost Catron County, less than a mile north of the Grant County line. Unfortunately, the Big Dry Creek *Teleoceras* skull has been lost for many years. This specimen was part of the Cope Collection and was cataloged as AMNH 8397; however, attempts to locate the skull in the AMNH were unsuccessful (written communication by Earl Manning to Winfried Leopoldt, July 10, 1980, in Leopoldt 1981). The identification of *T. fossiger* follows Cope’s 1884 paper. Several other species of *Teleoceras* are known from late Hemphillian faunas, including *T. guymonense* and *T. hicksi* (Prothero 2005).

In May 1997, Andrew Heckert of the NMMNH found a fragment of a proboscidean mandible with a partial m3 (NMMNH locality L-3468; catalog number NMMNH 26677), tentatively identified as the typical late Hemphillian gomphothere genus *Rhynchotherium*, from a conglomeratic unit of the Gila Group in Dugway Canyon, about 6 km southeast of Glenwood and 3 km northeast of Cope’s locality on Big Dry Creek. A partial pelvis of a large rabbit (catalog number NMMNH 26678) was found in this same area. In October 2000, Ken Kietzke of the NMMNH collected the lower second molar (m2) of the horse *Neohipparion eurystyle* (NMMNH locality L-4615; catalog number NMMNH 31597; Figs. 3M, 3N) in an indurated conglomerate of

the Gila Group at the base of a roadcut on the east side of US Route 180, just north of Glenwood. Measurements of NMMNH 31597 are length, 22.7 mm; width, 12.5 mm; crown height, 66.6 mm. *Neohipparion eurystyle* is characteristic of late Hemphillian (late Miocene and earliest Pliocene) faunas in Florida and the southern Great Plains (Hulbert 1987). The Glenwood tooth of *N. eurystyle* and several associated teeth of *N. gidleyi* from the late Hemphillian Lyden Quarry from the Chamita Formation in northern New Mexico (MacFadden 1984b) represent the only records of tridactyl (three-toed) horses from the late Hemphillian of New Mexico. Most other horses of this age belong to the monodactyl (one-toed) equine genera *Astrohippus* and *Dinohippus*, including *A. ansae* and *D. interpolatus* from the late Hemphillian San Juan and Rak Camel Quarries from the Chamita Formation (MacFadden 1977) and *A. stockii* and *D. mexicanus* from the latest Hemphillian Walnut Canyon LF (Morgan et al. 1997).

The occurrence of the Glenwood Fauna above the 5.6 Ma Harve Gulch basalt and the presence of *Teleoceras fossiger* and *Neohipparion eurystyle* both suggest a late Hemphillian age. Although similar in age to the Walnut Canyon LF located about 60 km farther southeast, the two faunas do not share any species of age-diagnostic mammals and there is no direct lithostratigraphic correlation between the coarse-grained conglomeratic sediments of the Gila Group near Glenwood and the finer-grained Gila Group strata in the Walnut Canyon area. Differences in the composition of the Glenwood and Walnut Canyon mammal assemblages suggest slight disparities between the two faunas in either age or paleoecology. The large mammals from the Glenwood Fauna, *Teleoceras*, *Neohipparion*, and a gomphothere, indicate a mesic savanna fauna. Walnut Canyon is dominated by one-toed horses and camels, with an absence of rhinos, three-toed horses, and mastodons, suggesting a more xeric grassland habitat.

Pliocene and Early Pleistocene Vertebrate Faunas (Blancan NALMA)

Buckhorn

A diverse vertebrate fauna of Pliocene (Blancan NALMA) age, the Buckhorn Fauna, has been recovered from Gila Group strata northwest of Buckhorn in northern Grant County (Figs. 1, 2D). Most of the fossils are derived from badlands along the northeast side of Duck Creek, from 3 to 5 km northwest of Buckhorn. There are several additional localities 8 to 10 km northwest of Buckhorn and one locality about 8 km northeast of Buckhorn. The main series of Buckhorn sites are located about 30 km northwest of the Walnut Canyon Horse Quarry. Blancan fossils of the Buckhorn Fauna occur at four stratigraphic levels within about a 50 m thick interval in the upper part of the Gila Group near Duck Creek (Morgan et al. 1997). Greenish mudstones near the base of the Duck Creek section have produced a few fossils of camels and birds. A fine, grayish sand somewhat higher in the section contains numerous microvertebrates, including rodents, birds, snakes, frogs, and fish. Fossils of camels

and a proboscidean occur in overlying reddish mudstones. A light-colored, clayey sand about 15 m higher in the section has yielded a partial skeleton and several limb bones of a flamingo and several smaller waterbirds. Fine-grained strata in the vicinity of Buckhorn were considered the lacustrine facies of the upper Gila Group (= Gila Formation), associated with Pliocene Lake Buckhorn (Mack and Stout 2005). The diverse aquatic component of the vertebrate fauna, including waterbirds at several stratigraphic levels, as well as fish, frogs, and salamanders from the Buckhorn microvertebrate quarry, are consistent with the deposition of much of the Buckhorn Fauna either in or along the shores of a permanent lake.

Vertebrate fossils were first found in the vicinity of Buckhorn in 1953 by George Pearce, a field paleontologist for the Frick Laboratory of the American Museum of Natural History (AMNH). Pearce collected fossils from a locality he described as "5 miles northwest of Buckhorn." No other locality or stratigraphic data are available for Pearce's Buckhorn site. Gary Morgan, Paul Sealey, and NMMNH field crews collected fossils from Pliocene outcrops in the Buckhorn area on six field trips in the mid 1990s. They made several unsuccessful attempts to relocate Pearce's site, prospecting virtually all of the Gila Group exposures between about 3 and 10 km northwest of Buckhorn. Leopoldt (1981, p. 129) also noted that "all efforts to locate this site accurately were unsuccessful." NMMNH field crews discovered about a dozen new Blancan localities, mostly in the area 3 to 5 km northwest of Buckhorn along Duck Creek, but none of these matched Pearce's original site in the composition of the fauna or preservation of the fossils. The most common large mammal in Pearce's Buckhorn Fauna is the horse *Equus*, whereas the camel *Hemiauchenia* is common in the NMMNH Buckhorn sites and horses are rare. Based on the Blancan age of the mammalian faunas and the occurrence of these sites in fine-grained sediments of the Gila Group in the general vicinity of Buckhorn, Morgan et al. (1997) combined the Pearce Buckhorn site with the NMMNH Buckhorn sites as the Buckhorn Fauna. Sometime after Pearce made his collection and before the NMMNH collections were made, a geologist working for the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) in Socorro discovered small samples of Pliocene vertebrate fossils at two sites near Buckhorn. One site about 8 km northwest of Buckhorn produced a partial skeleton of the small canid *Canis lepophagus* and another site about 6 km northeast of Buckhorn in Little Pat Canyon yielded a toe of the large camel *Camelops* and several associated postcranial elements of a rabbit. These fossils have excellent locality data, but the collector and date were not recorded. The fossils probably were found during the 1980s because much of the NMBGMR vertebrate paleontology collection was accumulated during that decade. The NMBGMR collection was transferred to the NMMNH in 1994, but the Buckhorn fossils were not discovered until after the Buckhorn LF was described (Morgan et al. 1997).

Prior to the description of the Buckhorn Fauna (Morgan et al. 1997), several authors mentioned fossils from Pearce's

Buckhorn collection in the F:AM/AMNH. Steadman (1980) identified the fossil turkey *Meleagris*. Tedford (1981) reported the horses *Nannippus* and *Equus* cf. *E. simplicidens* and the camels *Camelops* and *Hemiauchenia* cf. *H. blancoensis*, as well as carnivores, rabbits, rodents, peccaries, and mastodons. He noted that the joint occurrence of *Nannippus* and *Equus* cf. *E. simplicidens* indicated a medial Blancan age for the Buckhorn Fauna. In a master's thesis on the geology of the Mangas graben, Leopoldt (1981) listed the fossil mammals from Pearce's Buckhorn site based on identifications by Richard Tedford and Earl Manning. In addition to the taxa reported by Tedford (1981), Leopoldt mentioned an ursid, the cat *Felis* sp., the badger *Taxidea* cf. *T. taxus*, an unidentified ruminant (cervid or antilocaprid), the ground squirrel *Spermophilus* sp., and a rabbit. In a review of North American Neogene avian localities, Becker (1987) listed ducks (Anatidae) and *Meleagris* from Pearce's Buckhorn site.

The Buckhorn Fauna is composed of 29 species of vertebrates: 1 fish; 1 frog; 1 salamander; 2 snakes; 6 birds; and 18 mammals, including 1 bat, 5 carnivores, 2 horses, 1 peccary, 2 camels, 1 ruminant, 1 proboscidean, 4 rodents, and 1 lagomorph (Morgan et al. 1997; Table 2). Typical vertebrate fossils from the Buckhorn Fauna are illustrated in Figure 4. Frogs of the genus *Lithobates* (formerly *Rana*) are the most common vertebrates in the Buckhorn microvertebrate quarry (NMMNH locality L-2912), represented by more than 100

Table 2. Pliocene (late early Blancan) vertebrates from the Buckhorn Local Fauna, Gila Group, Mangas basin, Grant County, southwestern New Mexico. Genera are listed alphabetically within a family. Taxa that could eventually be identified with further study are listed as undet. (undetermined), whereas taxa that lack adequate material for a more precise identification are listed as indet. (indeterminate). The symbol † designates an extinct species.

Osteichthyes
family, genus, and species undet.

Amphibia

Anura

Ranidae

Lithobates (= *Rana*) sp.

Urodela

Ambystomatidae

Ambystoma sp.

Reptilia

Squamata: Serpentes

Colubridae

genus and species undet.

(more than one species present)

Aves

Anseriformes

Anatidae

genus and species undet.

(two species present)

Table 2 (cont'd)

Galliformes

Phasianidae

cf. *Meleagris* sp.

Charadriiformes

Phoenicopteridae

Phoenicopiterus sp.

Gruiformes

Rallidae

cf. *Rallus* sp.

Passeriformes

family, genus, and species undet.

Mammalia

Chiroptera

Vespertilionidae

genus and species indet.

Carnivora

Canidae

†*Canis lepophagus*

Felidae

Felinae

genus and species indet.

Machairodontinae

genus and species indet.

Mustelidae

Taxidea sp.

Ursidae

genus and species indet.

Perissodactyla

Equidae

†*Equus simplicidens*

†*Nannippus peninsulatus*

Artiodactyla

Tayassuidae

cf. *Platygonus* sp.

Camelidae

Camelops sp.

†*Hemiauchenia blancoensis*

Ruminantia: Antilocapridae or Cervidae

family, genus, and species indet.

Proboscidea

Gomphotheriidae

cf. *Stegomastodon* sp.

Lagomorpha

Family Leporidae

genus and species indet.

Rodentia

Sciuridae

†*"Spermophilus" bensoni*

Cricetidae

Baiomys sp.

†*Repomys panacaensis*

Arvicolidae

†*Ogmodontomys poaphagus*



Fig. 4. Photographs of vertebrate fossils from the early Pliocene (early Blancan NALMA) Buckhorn Local Fauna, Grant County, New Mexico. A. Associated wing elements of an extinct species of the flamingo *Phoenicopterus* (NMMNH 26664). B. Assorted fossils of the frog *Lithobates* (= *Rana*), except for the vertebra in the lower right corner, which is from a snake (Serpentes: Colubridae). C. Medial view and D. occlusal view, *Ogmodontomys poaphagus*, left mandible with m1-m3 (NMMNH 26720). D. Proximal phalanges of three camels: left, *Camelops* (NMMNH 56805); center,

Hemiauchenia blancoensis (NMMNH 26648); right, small species of *Hemiauchenia* (NMMNH 26628). E. Lateral view and F. occlusal view, *Canis lepophagus*, left mandible with p4-m2 (NMMNH 56802). G. *Canis lepophagus*, fragment of left maxilla with partial P4 and M1-M2 (NMMNH 56802). H. *Canis lepophagus*, associated right metacarpals 3–5 (NMMNH 56802). Each of the blue-and-white squares on the scales is 1 cm in width. The lengths of other scales are labeled individually.

specimens, far outnumbering all other species in that site (Fig. 4B). With the exception of birds, all records of lower vertebrates (i.e., non-mammals) from the Buckhorn LF are from the microvertebrate quarry, including fish, frogs, salamanders, and snakes. Birds are fairly common in several other Buckhorn sites, especially waterbirds, including a flamingo, a rail, and ducks. The presence of the flamingo *Phoenicopterus* is particularly intriguing (Fig. 4A), indicating a wetter environment with a large lake (Lake Buckhorn) and possibly warmer climatic conditions. The absence of both freshwater turtles and land tortoises from the Buckhorn sites is puzzling, considering the freshwater depositional environment favored by turtles and the abundance of land tortoises in other New Mexico Blancan faunas.

The most common large mammal in the Buckhorn Fauna is a member of the camel family, the long-limbed llama *Hemiauchenia*, tentatively referred to the species *H. blancoensis*. Another member of the llama tribe, *Camelops* is represented by a small sample of postcranial elements that are much larger and more robust than *Hemiauchenia* (Fig. 4D). There are two species of horses in the Buckhorn LF, the small three-toed horse *Nannippus peninsulatus* and the larger one-toed horse *Equus simplicidens*, both represented by diagnostic teeth and postcranial bones. Most other ungulates are rare, including a peccary, possibly the extinct genus *Platygonus*, and a ruminant artiodactyl, either a deer or pronghorn. The most complete specimen in the Buckhorn Fauna is a partial skeleton of the extinct coyote-like canid *Canis lepophagus* (catalog number NMMNH 56802), represented by a partial maxilla with P4-M2, left lower jaw with p4-m2, a partial forelimb with radius, ulna, metacarpals, carpals, toes, and a half dozen vertebrae (Figs. 4E–H). The badger *Taxidea* is known from a lower jaw with a nearly complete dentition. Other carnivores include a large sabercat, a smaller cat, and a bear, all represented by isolated postcranial elements that are non-diagnostic at either the genus or species level.

A significant sample of small mammals was recovered by screenwashing several hundred kilograms of unconsolidated fine, grayish sand from the Buckhorn microvertebrate quarry. The most common small mammal in this quarry is *Ogmodontomys poaphagus*, an extinct genus and species of arvicoline or microtine rodent (Fig. 4C). Teeth and/or jaws of several other small mammals are known from the Buckhorn microvertebrate quarry, including a single tooth of *Repomys panacaensis*, an extinct genus and species of small rodent possibly related to woodrats; several lower jaws and a maxilla of an extinct species of the pygmy mouse *Baiomys*; and a lower molar of a small insectivorous bat. Small mammals from Pearce's Buckhorn site include several associated postcranial elements of a rabbit and a lower jaw with two molars of a ground squirrel referred to the extinct Blancan species "*Spermophilus bensoni*". "*Spermophilus*" is placed in quotes because a recent taxonomic revision of this genus (Helgen et al. 2009) elevates eight previously recognized subgenera of *Spermophilus* to the generic level. It is not clear to which of these subgenera (now genera) the species *bensoni* belongs.

Many mammals from Buckhorn are indicative of Pliocene

(Blancan) faunas, including the canid *Canis lepophagus*, the horses *Nannippus peninsulatus* and *Equus simplicidens*, the camel *Hemiauchenia blancoensis*, and the rodents *Spermophilus bensoni*, *Ogmodontomys poaphagus*, and *Repomys panacaensis*. Moreover, the presence of several of these species permits a more precise placement within the Blancan NALMA. The co-occurrence of *Nannippus peninsulatus* and *Equus simplicidens* indicates that the Buckhorn LF is older than 2.6 Ma, as there are no records of either of these horses in New Mexico Blancan faunas younger than the boundary between the Gauss and Matuyama geomagnetic chrons at 2.58 Ma. A pre-late Blancan age (older than 3.0 Ma) is further suggested by the absence in the Buckhorn Fauna of immigrants from South America (e.g., glyptodonts, mylodont ground sloths) that reached North America during the Great American Biotic Interchange in the early late Blancan (about 3.0–2.6 Ma). The presence of *Equus simplicidens* and *Camelops* excludes earliest Blancan faunas (older than 4 Ma; Lindsay et al. 1984). *Spermophilus bensoni* was originally described from the late early Blancan Benson Fauna in southeastern Arizona (Gidley 1922). The evolutionary stage of two other rodents from the Buckhorn LF, *Ogmodontomys poaphagus* and *Repomys panacaensis*, is also consistent with a late early Blancan age (between 4.0 and 3.0 Ma) for the Buckhorn Fauna. Broadly correlative early Blancan faunas from the southwestern United States are Arroyo de la Parida, Cuchillo Negro Creek, Mesa del Sol, Tonuco Mountain, and Truth or Consequences in the Rio Grande Valley of New Mexico (Morgan and Lucas 2003a; Morgan et al. 2011) and Benson, Clarkdale, Duncan, and Verde in Arizona (Czaplewski 1987, 1990; Tomida 1987; White and Morgan 2005). The Rexroad Fauna from Kansas, Beck Ranch in Texas, and Hagerman from Idaho are also similar in age (Bell et al. 2004).

Pearson Mesa and Virden

Two fossil vertebrate faunas from the late Blancan NALMA, the latest Pliocene Pearson Mesa LF and earliest Pleistocene Virden LF, have been collected from Gila Group sediments on Pearson Mesa in the eastern portion of the Duncan basin in the Gila River Valley south of Virden in northwestern Hidalgo County, New Mexico (Figs. 1, 5; Tomida 1987; Morgan and Lucas 2000; Morgan et al. 2008). Strata on Pearson Mesa containing the Pearson Mesa and Virden faunas extend westward a mile or so into Greenlee County in southeastern Arizona. The fossils are derived from two stratigraphic intervals within a 70 m thick section of sandstones and mudstones of the Gila Group on Pearson Mesa (Morgan et al. 2008), interpreted as alluvial-fan or alluvial-flat deposits (Mack 2004). Tedford (1981) first mentioned Blancan vertebrate fossils from the Gila Group in the Duncan basin near Virden; however, the mammals he listed are mostly from the Duncan Fauna of medial (= late early) Blancan age in the western portion of the basin near the towns of Duncan and Clifton in Arizona (Tomida 1987), not from Pearson Mesa. Tomida (1987) listed the fauna from Pearson Mesa, including five taxa of mammals, and also measured a stratigraphic section and sampled five paleomagnetic sites. Morgan and Lucas

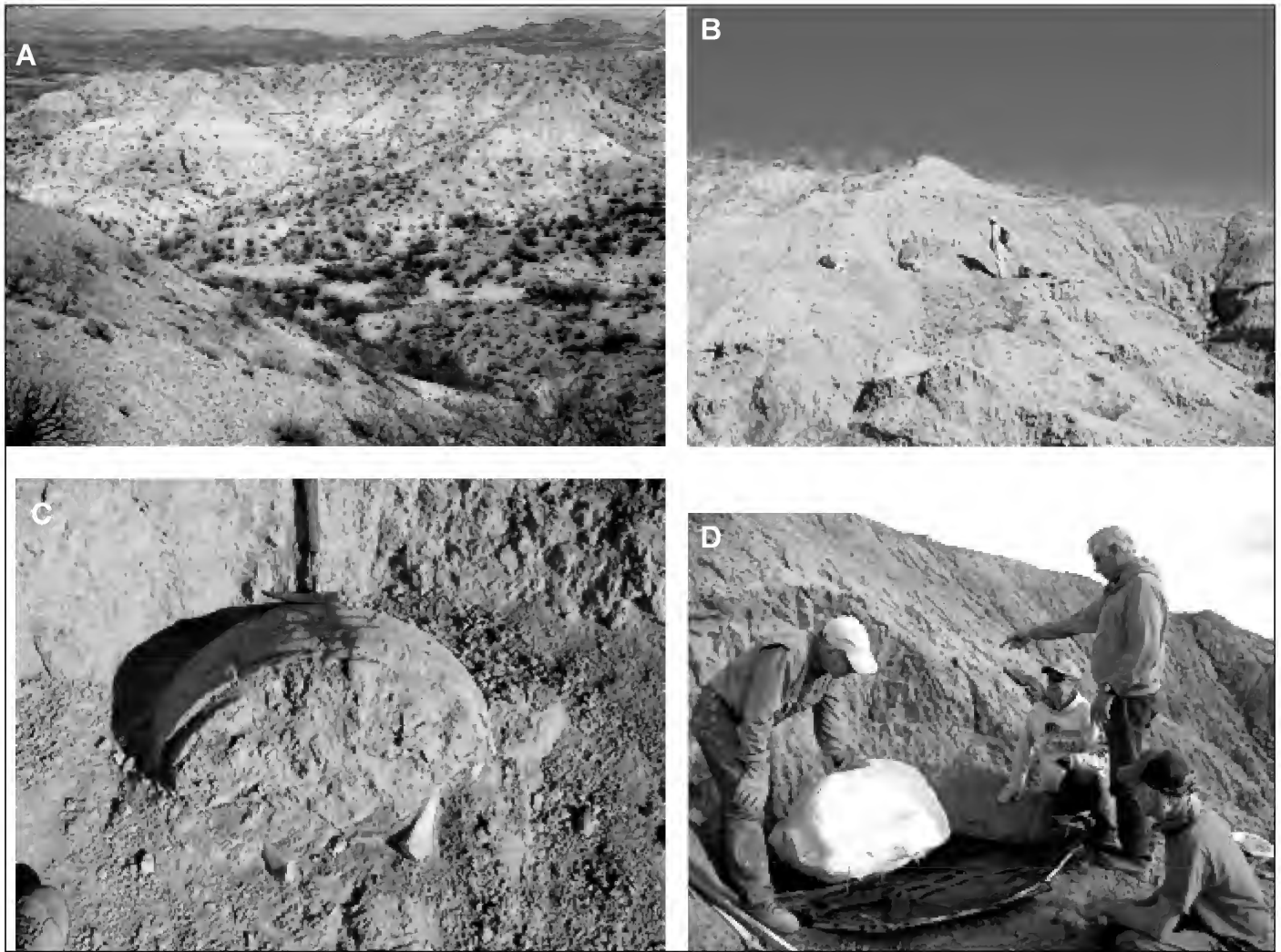


Fig. 5. Photographs of Gila Group outcrops and fossils on Pearson Mesa, Duncan basin, Hidalgo County, New Mexico. A. Gila Group outcrops on Pearson Mesa. B. Paleontologists examine site in the early Pleistocene (latest Blancan) Virden Fauna containing a shell of the giant land

tortoise *Hesperotestudo*. C. Partially excavated in situ shell of *Hesperotestudo* from the Virden Fauna. D. Paleontologists making a plaster jacket of *Hesperotestudo* shell from the Virden Fauna.

(2000, 2003a) summarized the Blancan vertebrate faunas from Pearson Mesa, and Morgan et al. (2008) presented a detailed review of the Pearson Mesa and Virden faunas.

New Mexico Museum of Natural History field crews first visited Pearson Mesa in 1998, discovering an abundant and diverse sample of Pliocene vertebrate fossils, including a concentration of fossil horses named the Pearson Mesa Horse Quarry (NMMNH locality L-3659). NMMNH crews collected fossils from the Pearson Mesa Horse Quarry and more than 100 other sites on Pearson Mesa on eight subsequent field trips between 1999 and 2012. Two vertebrate faunas occur on Pearson Mesa. The latest Pliocene (early late Blancan; about 3.0–2.6 Ma) Pearson Mesa LF is derived from the lower 15 m of the stratigraphic section and the earliest Pleistocene (latest Blancan; about 2.2–1.8 Ma) Virden LF occurs about 30 m higher in the section. There is very little overlap between the Pearson Mesa and Virden mammalian faunas, with only two shared species, a small dog and a large horse.

With the exception of the Pearson Mesa Horse Quarry, most of the Pearson Mesa sites have produced individual specimens of larger fossils, primarily mammals and land tortoises. A rich concentration of small vertebrates was discovered high in the section in strata referred to the Virden LF (NMMNH site L-6667). Screenwashing of about 500 kg of sediment from this site yielded 14 species of small vertebrates, including amphibians, reptiles, birds, and small mammals. Several other sites containing small vertebrates, including rodents and lagomorphs, occur lower in the section in the Pearson Mesa LF.

The Pearson Mesa LF consists of 26 species (Table 3): 3 land tortoises; 1 box turtle; 1 snake; 1 bird; and 20 mammals, including 1 glyptodont, 1 ground sloth, 3 carnivores (1 sabercat, 1 small cat, 1 small dog), 5 horses (4 one-toed horses, 1 three-toed horse), 5 artiodactyls (1 peccary, 2 camels, 1 pronghorn, 1 deer), 1 mastodon, 3 rodents, and 1 rabbit. Typical fossil vertebrates from the Pearson Mesa LF

Table 3. Late Pliocene and early Pleistocene (late Blancan) vertebrates from the Pearson Mesa and Virden local faunas, Gila Group, Duncan basin, Hidalgo County, New Mexico, and Greenlee County, Arizona. The Pearson Mesa LF is latest Pliocene (early late Blancan) and the Virden LF is earliest Pleistocene (latest Blancan). Genera and species are listed alphabetically within a family. Presence indicated by X, absence by —. An X followed by a ? (= cf. = referred) indicates that the species is tentatively referred because the fossil material present is either not sufficient for a positive identification or requires further study. Taxa that could eventually be identified with further study are listed as undet. (undetermined), whereas taxa that lack adequate material for a more precise identification are listed as indet. (indeterminate). The symbol † designates an extinct species.

	Pearson Mesa	Virden
Amphibia		
Anura		
family, genus, and species undet.	—	X
Reptilia		
Testudines		
Testudinidae		
<i>Gopherus</i> sp.	X	—
<i>Hesperotestudo</i> large species	X	X
<i>Hesperotestudo</i> small species	X	—
Emydidae		
<i>Terrapene</i> sp.	X	X
Squamata		
Serpentes		
Colubridae		
genus and species undet.	X	X
Sauria		
family, genus, and species undet.	—	X
Aves		
Ciconiiformes		
Ardeidae		
genus and species undet.	X	—
Galliformes		
family, genus, and species undet.	—	X
Passeriformes		
family, genus, and species undet.	—	X
Mammalia		
Cingulata		
Glyptodontidae		
† <i>Glyptotherium arizonae</i>	—	X
† <i>Glyptotherium</i> cf. <i>G. texanum</i>	X	—
Pilosa		
Mylodontidae		
† <i>Paramylodon garbanii</i>	X	—
Carnivora		
Felidae		
Felinae		
genus and species indet.	X	X
Machairodontinae		
genus and species indet.	X	—
Canidae		
† <i>Canis lepophagus</i>	X?	X
Perissodactyla		

(continued)

Table 3 (cont'd)

	Pearson Mesa	Virden
Equidae		
† <i>Equus calobatus</i>	X	—
† <i>Equus cummingsii</i>	X?	—
† <i>Equus scotti</i>	X	X
† <i>Equus simplicidens</i>	X	—
† <i>Nannippus peninsulatus</i>	X	—
Artiodactyla		
Tayassuidae		
† <i>Platygonus bicalcaratus</i>	X	—
Camelidae		
† <i>Hemiauchenia blancoensis</i>	X	X
† <i>Hemiauchenia gracilis</i>	—	X
<i>Hemiauchenia</i> sp.	X	—
Antilocapridae		
† <i>Capromeryx arizonensis</i>	X?	—
Cervidae		
genus and species indet.	X	—
Proboscidea		
Gomphotheriidae		
genus and species indet.	X	X
Rodentia		
Sciuridae		
genus and species undet.	—	X
Geomyidae		
† <i>Geomys (Nerterogeomys) persimilis</i>	X	X
Heteromyidae		
<i>Chaetodipus/Perognathus</i> sp.	X	—
Cricetidae		
<i>Baiomys</i> sp.	—	X
† <i>Bensonomys arizonae</i>	—	X?
<i>Neotoma</i> sp.	—	X
† <i>Sigmodon medius</i>	X	—
† <i>Sigmodon minor</i>	—	X
Lagomorpha		
Leporidae		
<i>Lepus</i> sp.	—	X?
<i>Sylvilagus</i> undescribed sp.	X	X

first described from a late Pliocene (late Blancan) site in the Texas Panhandle and later reported from the late Blancan of Arizona (Gillette and Ray 1981). A second xenarthran (order Pilosa) with South American affinities, the ground sloth *Paramylodon garbanii*, is represented in the Pearson Mesa Fauna by a femur collected in the Pearson Mesa Horse Quarry. *P. garbanii* is a rather small member of the ground sloth family Mylodontidae, which first appeared in southwestern faunas in the early late Blancan, although this species is known from somewhat older early Blancan faunas in Mexico, from which it was first described (Morgan 2008). Four species of horses have been identified from the Pearson Mesa Horse Quarry: three species of the genus *Equus*, *E. calobatus*, *E. cummingsii*, and *E. scotti*; and the three-toed horse *Nannippus peninsulatus*. A fourth species of *Equus*, *E. simplicidens*, occurs in another site in the Pearson Mesa LF but is not found in the Horse Quarry. The Pearson Mesa LF has the largest sample of the small hipparionine horse *Nannippus peninsulatus* known from New Mexico, with over 60 fossils, including 30 upper teeth, five lower jaws, and numerous postcranial elements, representing a minimum of six individuals. *Nannippus* is rare or absent in other New Mexico Blancan faunas. Another mammal rare in most New Mexico Blancan sites but common at Pearson Mesa is the large peccary *Platygonus bicalcaratus*. Pearson Mesa also has the largest sample of *P. bicalcaratus* known from the Blancan of New Mexico. Although not particularly common from Pearson Mesa, camels include a lower jaw of the large llama *Hemiauchenia blancoensis* and a partial skull and partial associated skeleton of a smaller unidentified species of *Hemiauchenia*. The small Blancan pronghorn *Capromeryx arizonensis* is tentatively identified from several postcranial elements. Small mammals are uncommon in the Pearson Mesa LF. The pocket gopher *Geomys persimilis* is known from a skull and several mandibles, the cotton rat *Sigmodon medius* from several lower jaws, and an extinct species of the living rabbit genus *Sylvilagus* from a partial skeleton.

are illustrated in Figure 6. Land tortoises are among the most common vertebrates encountered in the Pearson LF, including two species of the extinct genus *Hesperotestudo*, a fairly common species of giant tortoise and a much rarer smaller tortoise; and a large extinct species of the extant genus *Gopherus*, which contains the living desert and gopher tortoises. The glyptodont *Glyptotherium* cf. *G. texanum*, a giant armadillo-like herbivore belonging to mammalian order Cingulata of South American origin, was recently added to the Pearson Mesa LF based on fossils collected in 2012. The bony shell elements of this glyptodont, called osteoderms or scutes (Fig. 6D), have a very diagnostic pattern of grooves that resemble the osteoderms of the glyptodont *Glyptotherium texanum*,

The small Blancan pronghorn *Capromeryx arizonensis* is tentatively identified from several postcranial elements. Small mammals are uncommon in the Pearson Mesa LF. The pocket gopher *Geomys persimilis* is known from a skull and several mandibles, the cotton rat *Sigmodon medius* from several lower jaws, and an extinct species of the living rabbit genus *Sylvilagus* from a partial skeleton.

Many species of mammals from the Pearson Mesa LF are diagnostic of the Blancan NALMA, including the glyptodont *Glyptotherium* cf. *G. texanum*; the mylodont sloth *Paramylodon garbanii*; the horses *Nannippus peninsulatus*, *Equus* cf. *E. cummingsii*, and *E. simplicidens*; the peccary *Platygonus bicalcaratus*; the camel *Hemiauchenia blancoensis*; the pronghorn

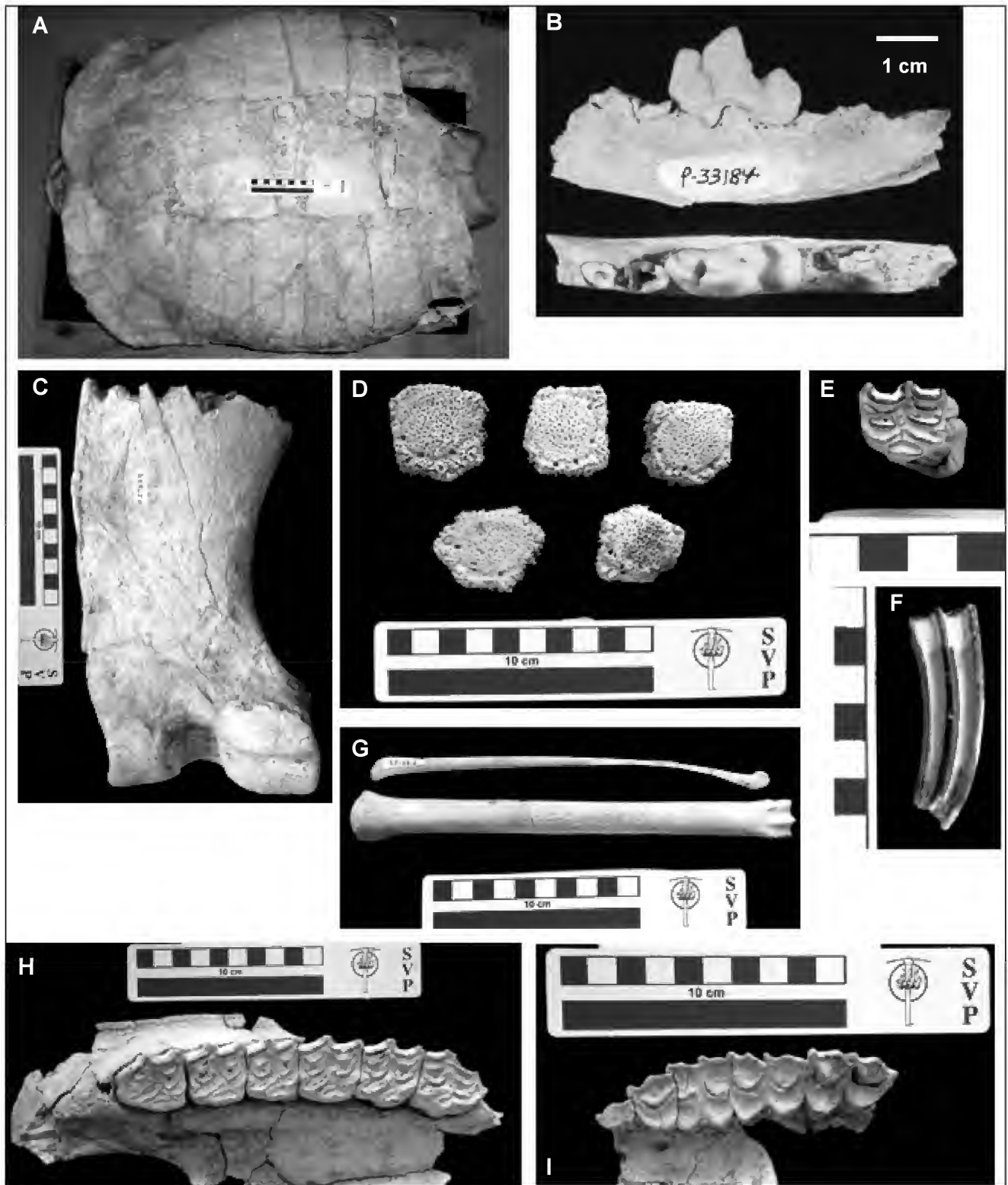


Fig. 6. Photographs of vertebrate fossils from the late Pliocene (late Blancan NALMA) Pearson Mesa Fauna (C–I) and early Pleistocene (latest Blancan) Virden Fauna (A–B), Gila Group, Hidalgo County, New Mexico. A. *Hesperotestudo*, dorsal view of nearly complete shell (NMMNH 55032). B. *Canis lepophagus*, lateral view (top) and occlusal view (bottom) of left mandible with m1 (NMMNH 33184). C. *Paramylodon garbanii*, posterior view of distal two-thirds of left femur (NMMNH 27639). D. *Glyptotherium* sp.,

osteoderms. E. Occlusal view and F. lateral view, *Nannippus peninsulatus*, left M2 (NMMNH 55077). G. *Nannippus peninsulatus*, anterior view of associated right metatarsal 2 (top) and metatarsal 3 (bottom, NMMNH 33183). H. *Equus* sp., occlusal view of palate with right P2–M3 (NMMNH 55093). I. *Hemiauchenia* sp., occlusal view of palate with left P3–M3 (NMMNH 55092). Each of the blue-and-white squares on the scales is 1 cm in width. The length of the scale bar in B is 1 cm.

Capromeryx arizonensis; and the rodents *Geomys persimilis* and *Sigmodon medius*. Several of these species have restricted biostratigraphic ranges within the Blancan, allowing for a more precise placement of the Pearson Mesa LF. *Nannippus peninsulatus* and *Equus simplicidens* occur in early late Blancan faunas (3.0–2.6 Ma) in New Mexico, but are not known from late Blancan faunas younger than about 2.6 Ma. South American immigrants that participated in the Great American Biotic Interchange, including *Glyptotherium texanum* and *Paramylodon garbanii*, first arrived in the southwestern United States at about 3.0 Ma. Thus, the co-occurrence of *Nannippus* and *Equus simplicidens* with *Glyptotherium* and *Paramylodon* defines a restricted interval of time after the arrival of glyptodonts and mylodont sloths about 3.0 Ma and before the extinction of *Nannippus* and *E. simplicidens* in New Mexico at about 2.6 Ma. Magnetostratigraphy further constrains the age of the Pearson Mesa LF. Tomida (1987) analyzed five normally magnetized samples from the stratigraphic interval that produced the Pearson Mesa LF, indicating referral of these strata to the uppermost Gauss Chron (3.04–2.58 Ma), strongly supporting the age suggested by the mammalian biostratigraphy. Southwestern early late Blancan faunas correlative with the Pearson Mesa LF include Anapra and Williamsburg from New Mexico, Wolf Ranch and 111 Ranch from Arizona, and Cita Canyon and Hudspeth from Texas (White and Morgan 2005; Morgan et al. 2008, 2011).

The Viriden LF consists of 22 species (Table 3): 1 toad; 1 land tortoise; 1 box turtle; 1 snake; 1 lizard; 2 birds; and 15 mammals, including 1 glyptodont, 2 carnivores (1 small cat, 1 small dog), 1 one-toed horse, 2 camels, 1 mastodon, 6 rodents, and 2 rabbits. Typical fossil vertebrates from the Viriden LF are illustrated in Figures 6A, 6B. A nearly complete shell and associated vertebrae and limb girdle elements of the large land tortoise *Hesperotestudo* were found in the Viriden LF (Morgan et al. 2008). Blancan *Hesperotestudo* from New Mexico and elsewhere in the Southwest are currently under study by Richard Franz. The Viriden LF contains a significant sample of small vertebrates from the Viriden microvertebrate quarry. Among lower vertebrates (i.e., non-mammals), the Viriden LF contains toads, snakes, lizards, and at least two species of birds, including a quail and a small perching bird. The most common small mammal in the Viriden microvertebrate quarry is the dwarf cotton rat *Sigmodon minor*. This site has also produced two species of lagomorphs, a large species of the jackrabbit *Lepus*, and a smaller undescribed species of the cottontail *Sylvilagus*. The undescribed *Sylvilagus* also occurs in the Pearson Mesa LF, and possibly in the late Blancan 111 Ranch and San Simon faunas from the Safford basin in Arizona (Tomida 1987). There are several individuals of the large glyptodont *Glyptotherium arizonae* from the Viriden LF. Osteoderms from *G. arizonae* are larger and thicker and have a slightly different pattern of grooves than a sample of osteoderms collected about 10 m lower in the section, tentatively identified as *G. texanum* and referred above to the Pearson Mesa LF. The taxonomy of Blancan glyptodonts from New Mexico and Arizona is currently under study (Dave Gillette et al. in prep.). Two mandibles from the Viriden LF are

referred to the ancestral coyote *Canis lepophagus*, a species typical of Blancan faunas but unknown from the Irvingtonian (Tedford et al. 2009). Based on the stratigraphic distribution of *C. lepophagus* (Tedford et al. 2009), the Viriden LF represents one of the youngest known records of this species. Horses are much less common and not nearly as diverse in the Viriden LF compared to the Pearson Mesa LF. Only one species is known, *Equus scotti*, compared to two genera and five horses from Pearson Mesa, including *E. scotti*. The small llama *Hemiauchenia gracilis* is represented in the Viriden LF by a pair of lower jaws. This rare species is known only from the Viriden and La Union faunas in New Mexico, one site in Arizona, and two sites in Florida, all latest Blancan in age (Meachen 2005; Morgan and White 2005).

Mammals from the Viriden LF typical of New Mexico late Blancan faunas include the glyptodont *Glyptotherium arizonae*, the canid *Canis lepophagus*, the horse *Equus scotti*, the camel *Hemiauchenia gracilis*, and the rodent *Sigmodon minor*. *Canis lepophagus* disappears at the end of the Blancan, whereas *Glyptotherium arizonae* and *Equus scotti* occur in both late Blancan and early Irvingtonian faunas. The two most age-diagnostic species in the Viriden LF, the small camel *Hemiauchenia gracilis* and the diminutive cotton rat *Sigmodon minor*, are both restricted to latest Blancan faunas (about 2.2–1.8 Ma). The type locality of *S. minor* is the latest Blancan Curtis Ranch Fauna in Arizona (Gidley 1922). Although *S. minor* has been synonymized with the larger *Sigmodon medius* from older Blancan faunas (Tomida 1987), *S. minor* is distinctly smaller and appears to be restricted to the latest Blancan. The absence of *Nannippus peninsulatus* from the Viriden LF is significant, especially considering that this species is quite common in the underlying Pearson Mesa LF. The local extinction of *Nannippus* apparently occurred during the 30 m thick unfossiliferous interval in the Pearson Mesa section between the Pearson Mesa and Viriden faunas. The paleomagnetic sampling by Tomida (1987) did not include the uppermost portion of the Pearson Mesa stratigraphic section containing the Viriden LF. Southwestern latest Blancan faunas correlative with the Viriden LF include Caballo and La Union from New Mexico and Curtis Ranch and San Simon from Arizona (Morgan and White 2005; Morgan et al. 2008, 2011).

Late Pleistocene Vertebrate Faunas (Rancholabrean NALMA)

Canovas Creek

The Canovas Creek Local Fauna (NMMNH locality L-8175) is located in northwestern Catron County in west-central New Mexico, about 3 km east of the Arizona border (Figs. 1, 7). The site is named for Canovas Creek, a dry wash about 6 to 8 m deep that trends in a northwest to southeast direction about 100 m north of the fossil site. Canovas Creek is one of the highest Pleistocene fossil sites in New Mexico, at an elevation of 2,375 m (7,793 ft). The site is located in the Apache National Forest on land administered by the Gila National Forest through the US Forest Service (USFS) in Silver City, New Mexico.

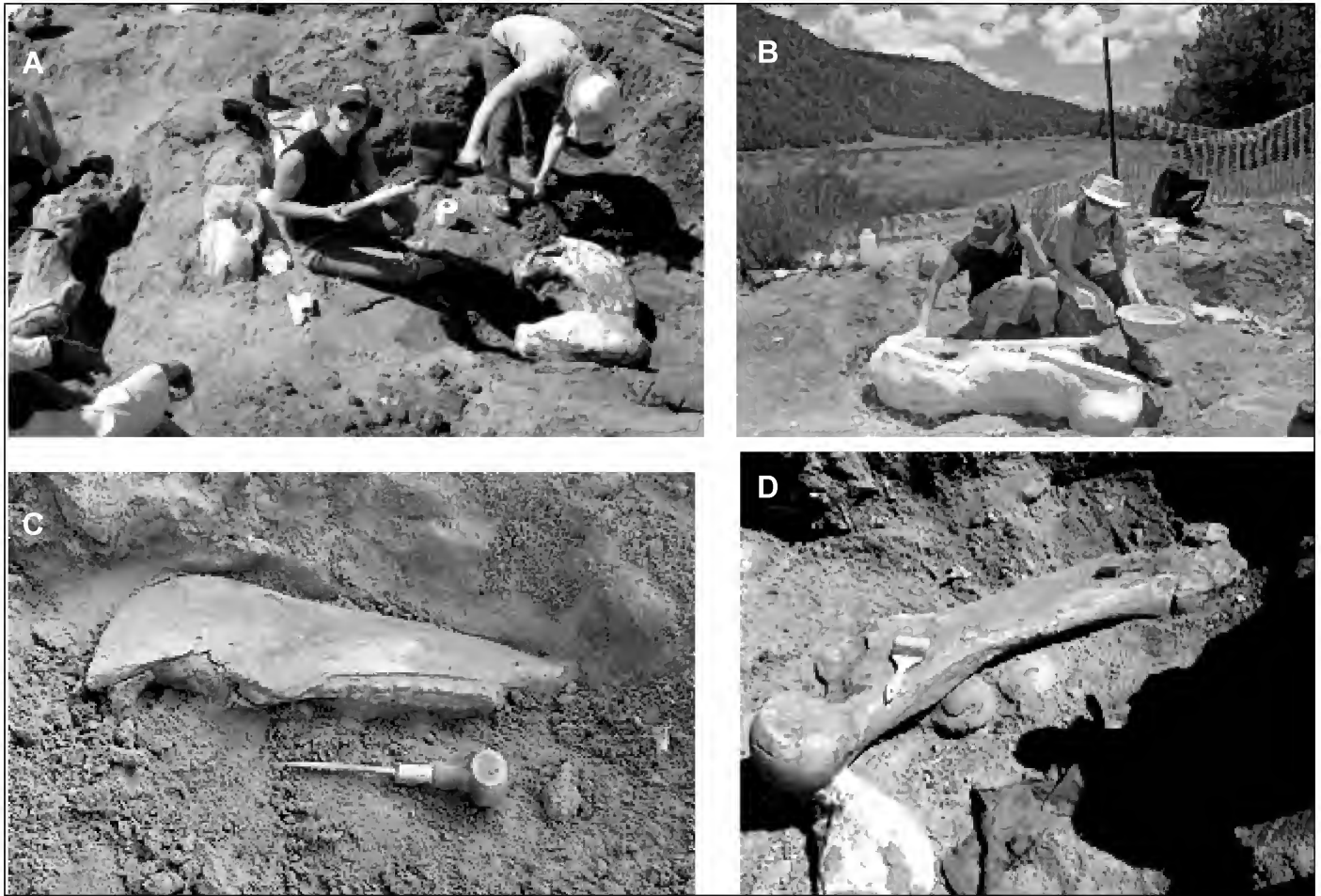


Fig. 7. Photographs of the late Pleistocene (Rancholabrean NALMA) Canovas Creek site, Catron County, New Mexico. A. Paleontologist in the center of photo is holding the recently collected radius of a small horse (*Equus conversidens*). Paleontologist on the right is excavating around a plaster jacket containing the mandibles of a Columbian mammoth

(*Mammuthus columbi*). At the left edge of the photo is a humerus of *Mammuthus columbi* (same humerus is being jacketed in B). B. Two paleontologists plaster jacketing the humerus of *Mammuthus columbi*. C. Lower jaw of *Equus conversidens* in situ, awl for scale. D. Femur of *Mammuthus columbi* in situ, paint brush for scale.

The Canovas Creek site was discovered in September 2010 by Chris Wonderly, a local resident who was collecting firewood at the time. He drove over a “rock” in the middle of a USFS road with his truck, and upon getting out to retrieve several pieces of firewood noticed that the rock was actually a piece of a mammoth tusk. He also found several other fossils in the road in the immediate vicinity of the tusk, including a horse jaw with several teeth. Mr. Wonderly documented his find with photographs and reported his discovery to the USFS. Shortly thereafter, Christie Lucero, a paleontology volunteer at the New Mexico Museum of Natural History in Albuquerque (NMMNH) and member of the New Mexico Friends of Paleontology (NMFOP), contacted me about Mr. Wonderly’s discovery. I obtained permits from the USFS to conduct excavations at the Canovas Creek site from 2011 to 2013. Field crews from the NMMNH, consisting of from 3 to 10 people, have excavated the Canovas Creek LF over three field seasons, from September 2011 to October 2013,

including seven separate trips and about 75 person days of combined field effort. At this writing, field work is continuing at the Canovas Creek site, with completion of the excavation planned by the end of the 2014 field season.

The Canovas Creek site consists of a concentrated layer of vertebrate fossils about 20 to 50 cm in thickness occurring over an area of about 25 m². The fossiliferous layer is mostly located between 0.5 m and 1.0 m below the current land surface, although several fossils, including a partial mammoth tusk, were exposed at the surface in the ruts of a two-track USFS road. In general, the fossil layer is closer to the surface in the eastern portion of the site and angles or dips gently downward toward the west, reaching a meter or more in depth on the western edge of the site. Most of the fossils occur in a brown fine sand, with some silt and clay and occasional large rounded boulders of volcanic rock up to 30 cm in diameter. In the center of the site the fossil layer is about 1 m below the current land surface and the sediments are coarser,

consisting of medium to coarse sand with a much-reduced component of fine sand, silt, and clay, perhaps representing the bottom of a paleochannel feature.

Almost all of the fossils in the Canovas Creek site consist of isolated elements, the most common of which are hundreds of isolated teeth and postcranial bones of an extinct species of small one-toed horse, *Equus conversidens*. Besides isolated teeth, sturdy bones such as carpals, tarsals, and toes, as well as vertebrae, are particularly well represented. Numerous complete larger fossils are present as well, including nearly 20 jaws and about a dozen intact limb bones of horses and a pair of lower jaws, an isolated molar, and several limb bones of the mammoth *Mammuthus*. Overall, intact fossils are less common than incomplete and broken bones. In addition to the hundreds of well-preserved fossils in the Canovas Creek site, there are also thousands of unidentifiable bone fragments. Durable fossils such as horse limb bones and isolated teeth are often broken, consisting of old breaks that occurred near the time of deposition. There are essentially no articulated elements, although some association was observed. For example, about 20 teeth and postcranial bones of the extinct camel *Camelops hesternus* were found in a small area of the site less than 0.5 m², although no articulation was evident in the field. Camels are otherwise rather uncommon in the site, strongly suggesting that most of these elements represented a single adult individual of *Camelops* that became interred in one small area of the site.

The lack of articulated remains, abundance of broken and fragmentary fossils, and numerous waterworn bones suggest that the Canovas Creek site consists of a transported assemblage. Apparently, the primary site of deposition was elsewhere. The fossils were transported by water under high-energy conditions, perhaps a flash flood, and secondarily redeposited in their current location. The rarity of fossils representing freshwater species (no fish, frogs, or salamanders, and one mud turtle shell fragment) suggests that the site of deposition was not a permanent water source such as a pond, lake, or stream.

The Canovas Creek Local Fauna consists of 18 species: the small mud turtle *Kinosternon*, 2 birds, and 15 mammals (Table 4). Typical mammalian fossils from the Canovas Creek LF are illustrated in Figure 8. There are five members of the extinct Pleistocene fauna: the horses *Equus conversidens* and *E. occidentalis*, the large camel *Camelops hesternus*, the pronghorn *Stockoceros* sp., and the Columbian mammoth *Mammuthus columbi*. There are two medium-sized species of carnivores, the bobcat *Lynx rufus* and the coyote *Canis latrans*, both of which still live in the Gila Region. Small mammals consist of eight species: a shrew (*Sorex* sp.); five rodents, including a ground squirrel (*Urocitellus* cf. *U. elegans*), red squirrel (*Tamiasciurus hudsonicus*), the northern pocket gopher (*Thomomys talpoides*), a woodrat (*Neotoma* sp.), and a vole (*Microtus* sp.); and two rabbits, a jackrabbit (*Lepus* sp.) and mountain cottontail (*Sylvilagus nuttallii*).

The Canovas Creek Fauna is dominated by a small species of *Equus*, the Mexican horse *E. conversidens*, including several partial skulls, about a dozen lower jaws, several hundred

Table 4. Late Pleistocene (Rancholabrean) vertebrates from the Canovas Creek Local Fauna, Catron County, New Mexico. The symbol † designates an extinct species.

Reptilia	
Testudines	
Kinosternidae	
<i>Kinosternon</i> sp.	
Aves	
2 unidentified species	
Mammalia	
Lipotyphla	
Soricidae	
<i>Sorex</i> sp.	
Carnivora	
Canidae	
<i>Canis latrans</i>	
Felidae	
<i>Lynx rufus</i>	
Perissodactyla	
Equidae	
† <i>Equus conversidens</i>	
† <i>Equus occidentalis</i>	
Artiodactyla	
Camelidae	
† <i>Camelops hesternus</i>	
Antilocapridae	
† cf. <i>Stockoceros</i> sp.	
Proboscidea	
Elephantidae	
† <i>Mammuthus columbi</i>	
Rodentia	
Sciuridae	
<i>Tamiasciurus hudsonicus</i>	
<i>Urocitellus</i> cf. <i>U. elegans</i>	
Geomyidae	
<i>Thomomys talpoides</i>	
Cricetidae	
<i>Neotoma</i> sp.	
Arvicolidae	
<i>Microtus</i> sp.	
Lagomorpha	
Leporidae	
<i>Lepus</i> sp.	
<i>Sylvilagus nuttallii</i>	

isolated teeth, and at least a hundred postcranial elements. *E. conversidens* is the common small species of horse with stout metapodials found in late Pleistocene (Rancholabrean) faunas in New Mexico and western North America (Harris and Porter 1980; Wolberg 1980; Harris 1985; FAUNMAP Working Group 1994). This is the same species of small *Equus* referred to *E. alaskae* or the *E. alaskae* species group by other authors (Winans 1989; Harris 1993). *E. conversidens* generally is much less common in New Mexico Rancholabrean sites than is a larger species of *Equus*, referred to ei-

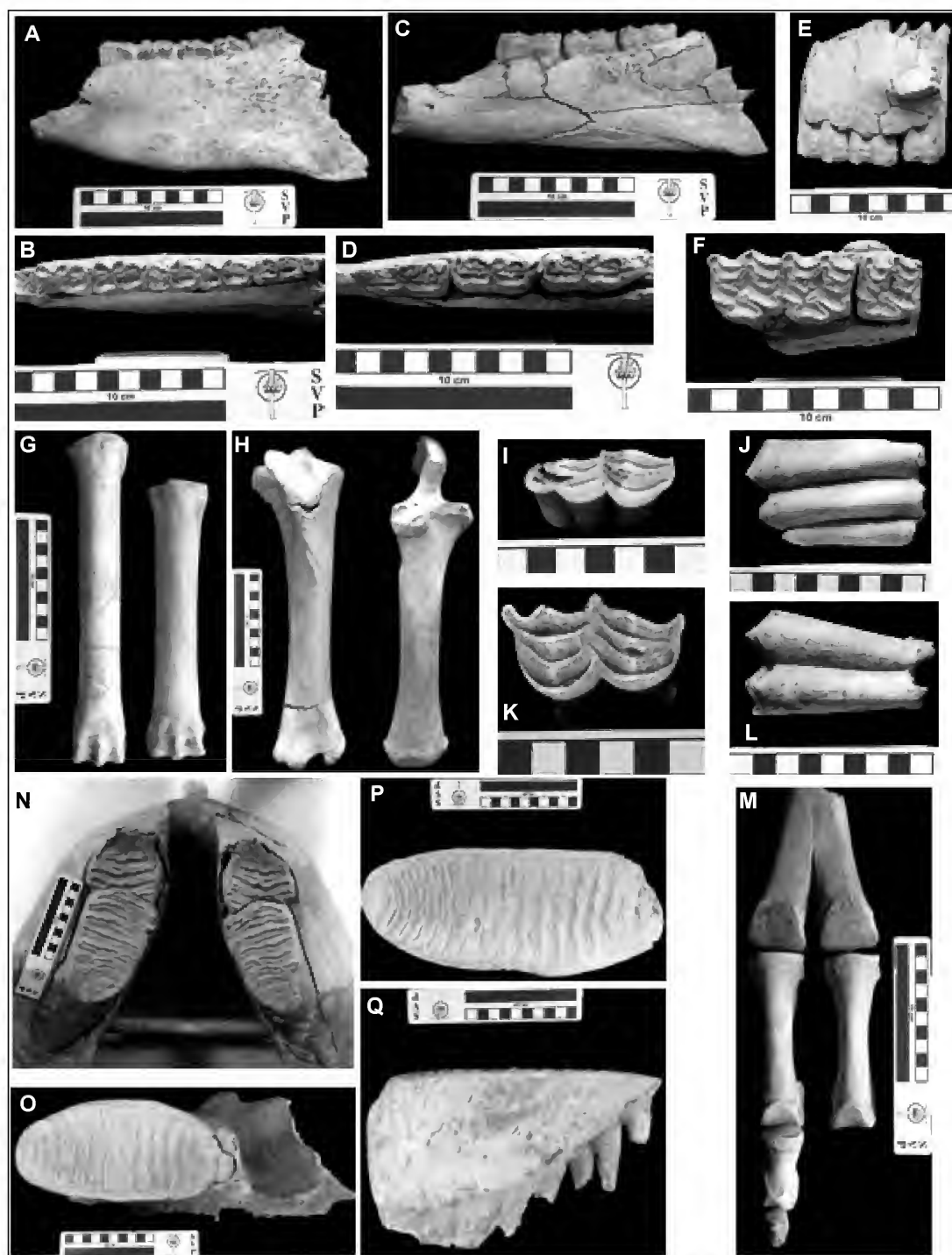


Fig. 8. Photographs of mammalian fossils from the late Pleistocene (Rancholabrean NALMA) Canovas Creek site, Catron County, New Mexico. A. Lateral view and B. occlusal view, *Equus conversidens*, left mandible with p3-m3 (NMMNH 67112). C. Lateral view and D. occlusal view, *Equus conversidens*, juvenile left mandible with dp2-dp4 (NMMNH 67113). E. Lateral view and F. occlusal view, *Equus conversidens*, fragment of left maxilla with P3-M1 (NMMNH 67114). G. Metatarsal (left, NMMNH 67110) and metacarpal (right, NMMNH 67105), *Equus conversidens*. H. Tibia (left, NMMNH 67111) and radius-ulna (right, NMMNH 67115), *Equus conversidens*. I. Occusal view and J. lateral view, *Camelops hesternus*, right m3 (NMMNH 67116). K. Occusal view and L. medial view, *Camelops hesternus*, left M2 (NMMNH 67117). M. *Camelops hesternus*, associated distal metapodial, two proximal phalanges, medial phalanx, and ungual phalanx-hoof (NMMNH 67119). N. *Mammuthus columbi*, occlusal view of mandibles with right and left m2-m3 (NMMNH 67107). O. *Mammuthus columbi*, occlusal view of right M3 in skull fragment (NMMNH 67108). P. Occusal view and Q. lateral view, *Mammuthus columbi*, left M3 (NMMNH 67109).

ther *E. niobrarensis* or *E. occidentalis* (Harris and Porter 1980; Morgan and Lucas 2005). The abundance of *E. conversidens* in the Canovas Creek Fauna suggests this site samples a different paleoenvironment than most other Pleistocene faunas in New Mexico, perhaps related to the higher elevation.

A second larger species of *Equus* is much less common than *E. conversidens* at Canovas Creek, represented by two lower jaws and several dozen isolated teeth and postcranial bones. This is the typical large horse found in late Pleistocene faunas in western North America (Harris 1985; FAUN-MAP 1994). Considerable controversy surrounds the proper species name for this large *Equus*. Winans (1989) used the name *E. laurentius* for large late Pleistocene *Equus* with stout metapodials; however, it has since been shown that the type specimen of this species is a modern domestic horse and thus *E. laurentius* is clearly an invalid name (Scott et al. 2010). Two other names, the niobrara horse *E. niobrarensis* and the western horse *E. occidentalis*, have often been used interchangeably in the literature for large late Pleistocene horses from New Mexico and elsewhere in western North America (e.g., Morgan and Lucas 2005). However, Harris and Porter (1980) recognized both of these large species of *Equus* from the late Pleistocene Dry Cave Fauna in southeastern New Mexico. Because it is the more widely used and recognized name, and is represented by a substantial sample from the Rancho La Brea tar pits in southern California (Merriam 1913), the name *E. occidentalis* is used here for the large horse from Canovas Creek, with the understanding that this name will likely change with further taxonomic work on Pleistocene horses from western North America.

The giant llama (also called yesterday's camel) *Camelops hesternus* is a large camel represented in the Canovas Creek site by at least three individuals representing juvenile, adult, and old adult animals. A concentration of *Camelops* fossils in a small area (about 1.0 m²) in the northwest quadrant of the locality is unusual, as camels are uncommon elsewhere in the Canovas Creek site. Two individuals of *Camelops* were collected from this general region of the site, including four associated upper teeth (P4-M3) of a mature adult and an associated upper premolar and two molars (P4-M2) of a young adult with higher crowned, less worn teeth. This area of the site also contained the distal portion of a limb of an adult *Camelops*, including the distal end of a metacarpal, two proximal phalanges, a single medial phalanx, and a single distal or ungual phalanx (hoof-supporting bone; Fig. 8M). The camel metacarpal and toes almost certainly pertain to one individual, as the bones were all found in the same general area and there is no duplication of elements. These camel postcranial elements compare very closely in size and morphology to a sample of *Camelops hesternus* from the late Pleistocene (Rancholabrean) White Mesa Mine in Sandoval County in northwestern New Mexico (Morgan and Rinehart 2007) and are also similar to a large series of *C. hesternus* from the Rancho La Brea tar pits in southern California (Webb 1965).

The Columbian mammoth *Mammuthus columbi* is also fairly common in the Canovas Creek Fauna, represented by as many as four individuals and about 25 fossils. The most

complete specimen is a pair of lower jaws (Fig. 8N), intact from the symphysis to the articular condyles and containing the heavily worn second molars (m2) and partially erupted third molars (m3) on both the right and left sides (NMMNH catalog number 67107). The m2s preserve only 5 enamel plates, are 72 mm long and 85 mm wide. The m3s are not fully erupted, with only 12 enamel plates in wear. The lamellar or plate frequency is 7 enamel plates per 100 mm of tooth length. It is difficult to count the total number of plates on the m3s, which must be in excess of 20, because the posterior portion of the teeth is unerupted and covered by the dentary bone. The portion of the m3s in wear is 145 mm in length and 85 mm in width; however, the total length of the m3 is estimated to be in excess of 400 mm.

Located very near the lower jaws were a skull fragment with an upper third molar (M3), an isolated M3, two partial tusks, and a femur, also of *Mammuthus columbi*. Despite their close proximity, these fossils do not all represent a single individual mammoth. A skull fragment with a fully erupted right M3 preserving the posterior edge of the alveolus for the tusk (NMMNH catalog number 67108) is from a mature individual. The specimen is from an older individual than the mammoth represented by the lower jaw because the jaw still preserves the m2 and the m3 is not fully erupted. Measurements of the M3 in the skull fragment (NMMNH 67108): 17 enamel plates; lamellar or plate frequency of 6 to 7 enamel plates per 100 mm of tooth length; total length 272 mm; maximum width 124 mm; maximum crown height 235 mm. The isolated M3 (NMMNH catalog number 67109) is also from a fully mature individual, with only the last two or three enamel plates unerupted. Measurements of the isolated left M3 (NMMNH 67109): 21+ enamel plates with 18 plates in wear; lamellar or plate frequency of 7 enamel plates per 100 mm of tooth length; total length, 319 mm; maximum width, 121 mm; maximum crown height, 184 mm. Both of the mammoth M3s described above have undergone some wear, so the length, total number of enamel plates, and crown height are all minimum values. Even though these two mammoth upper M3s were found within less than 1 m of each other, they appear to represent two individuals based on differences in size, number of enamel plates preserved, crown height, and color of preservation. The dental characters of the mammoth teeth from the Canovas Creek site, including the large number of enamel plates (17 to 21 plates or more), lamellar frequency of 6 to 7 enamel plates per 100 mm of tooth length, and comparatively thin, complicated enamel, are all advanced features typical of the large late Pleistocene species *M. columbi*.

In the southeast quadrant of the site, separated from the more complete mammoth specimens by about 10 m, we found a skull fragment with a poorly preserved tooth that represents a fourth individual. Other mammoth specimens include a complete humerus, two partial scapulae, astragalus, calcaneum, about a dozen vertebrae, and several toes. Several of the vertebrae have unfused epiphyses on the centra, indicating juvenile individuals. A nearly complete left femur (NMMNH 67123) is long and rather slender (length, 1450 mm; minimum shaft width, 220 mm), which separates it from

the American mastodon *Mammot americanum*, in which the femur is shorter and more robust.

An upper premolar and a lower second molar (m2) from Canovas Creek represent the pronghorn family Antilocapridae. These two teeth are larger than comparable teeth of the extinct dwarf pronghorn *Capromeryx furcifer* from New Mexico (White and Morgan 2011) and are tentatively referred to the larger extinct genus *Stockoceros*. *Stockoceros* has been reported from about 10 late Pleistocene cave deposits in New Mexico (Harris 1993, 2013), but the Canovas Creek specimens are the first record of this genus from an open site in the state.

The other 10 species of mammals in the Canovas Creek LF are still living. The coyote *Canis latrans* and the bobcat *Lynx rufus* are both represented by isolated teeth. These two medium-sized carnivores are still common in the Gila Region. It is difficult to explain the absence in the Canovas Creek Fauna of fossils representing large carnivores that would have preyed on the horses, camels, and mammoth, although several horse bones do possess large rounded bite marks that were clearly inflicted by carnivores larger than a coyote or bobcat. Several species of large extinct carnivores are known from other New Mexico late Pleistocene sites (Harris 1993), including dire wolf *Canis dirus*, American lion *Panthera atrox*, sabertooth cat *Smilodon fatalis*, and giant short-faced bear *Arctodus simus*.

Screenwashing of approximately 1 metric ton of sediment from the Canovas Creek site has yielded a fairly diverse small mammal fauna consisting of at least eight species represented by several hundred specimens of jaws, teeth, and postcranial bones. Surprisingly, no fish, amphibians (frogs, toads, and salamanders), or small reptiles (lizards and snakes) were recovered from the screenwashed sediments. Several bones of birds representing unidentified species of two different sizes were found during screenwashing. The most abundant small mammal in the Canovas Creek LF is the vole *Microtus*, a genus of small rodent found in montane habitats in New Mexico. Five species of *Microtus* are known from the modern fauna of New Mexico, most of which occur in the mountains above 2,000 m (Findley et al. 1975). Based on the range of sizes observed in the sample of lower first molars (m1) in the Canovas Creek sample, it seems likely that more than one species of *Microtus* is present. The species of *Microtus* are difficult to separate based on the fossil material present in the Canovas Creek site, mostly consisting of isolated teeth and a few lower jaws, and thus they are only identified to the genus level.

Three other species of small mammals are also fairly common at Canovas Creek, northern pocket gopher *Thomomys talpoides*, Wyoming ground squirrel *Urocitellus* cf. *U. elegans*, and mountain cottontail *Sylvilagus nuttallii*. Numerous isolated teeth from Canovas Creek, in particular several asymmetrical lower fourth premolars (p4), are identified as *Thomomys talpoides*. Northern pocket gophers occur primarily in meadows in montane forests in New Mexico and do not occur today in the immediate vicinity of Canovas Creek (Findley et al. 1975). The closest extant population of *T.*

talpoides is on Mount Taylor in Cibola County, about 250 km northeast of Canovas Creek. Late Pleistocene records of *T. talpoides* are known from half a dozen cave deposits in New Mexico, including several in the southern part of the state outside the modern range of the species (Harris 1993, 2013). Isolated teeth of a large ground squirrel are similar to teeth of *Urocitellus elegans*, a species no longer found in New Mexico. As noted above in the discussion of the extinct species "*Spermophilus*" *bensoni*, most ground squirrels in North America previously were referred to the genus *Spermophilus*. However, studies of their morphology, genetics, and phylogenetic relationships suggests that eight of the previously named subgenera of *Spermophilus*, including *Urocitellus*, are best recognized as full genera (Helgen et al. 2009). The Wyoming ground squirrel occurs from Idaho, Nevada, Montana, and Wyoming south to Utah, Colorado, and Nebraska, in mountain meadows above 1,500 m and also in sagebrush grasslands at lower elevations (Wilson and Ruff 1999). Although currently unknown south of central Colorado, *Spermophilus* (= *Urocitellus*) *elegans* has been reported from several late Pleistocene sites in New Mexico, including Dark Canyon Cave, Dry Cave, and Pendejo Cave in the southeastern part of the state and Sheep Camp Shelter in the northwestern part (Harris 1993, 2013). A small species of rabbit, identified as the mountain cottontail *Sylvilagus nuttallii*, is fairly common at Canovas Creek, represented by several lower jaws containing the diagnostic lower third premolar (p3), as well as half a dozen isolated p3s. The enamel pattern on the p3 and several measurements of the lower jaw can be used to separate *S. nuttallii* from two other species of *Sylvilagus* found in New Mexico, *S. audubonii* and *S. floridanus* (Findley et al. 1975). The distribution of *S. nuttallii* in New Mexico is currently limited to mountains in the northern part of the state (Findley et al. 1975), although mountain cottontails also occur in the White Mountains in east-central Arizona (Hoffmeister 1986) just to the west of the Canovas Creek site. *S. nuttallii* has been identified from more than 10 late Pleistocene cave deposits throughout New Mexico (Harris 1993, 2013), many of which are located in the southern part of the state, where this rabbit no longer occurs.

The other four species of small mammals identified from Canovas Creek, the shrew *Sorex*, the red squirrel *Tamiasciurus hudsonicus*, the woodrat *Neotoma*, and the jackrabbit *Lepus*, are each known from a small sample of fossils, and only the red squirrel is represented by diagnostic material identifiable to the species level. There are eight species of long-tailed shrews of the genus *Sorex* known from the modern fauna of New Mexico, most of which occur at higher elevations in the mountains of northern New Mexico (Findley et al. 1975; Harris 2013). The shrew that occurs today nearest to Canovas Creek, the montane shrew *Sorex monticolus*, generally is found in the mountains above 2,200 m and is known from the Zuni Mountains and Mount Taylor north of the fossil site and the Mogollon Mountains south of Canovas Creek (Findley et al. 1975). Two partial lower jaws of *Sorex* from the Canovas Creek site are not complete enough to allow a species identification. Although known from a small sample

of isolated teeth, the size and dental characters of teeth representing a small sciurid are a close match for the red squirrel *Tamiasciurus hudsonicus*. The red squirrel is found in mixed-coniferous and spruce-fir forests in New Mexico, generally above 2,400 m (Findley et al. 1975). *T. hudsonicus* does not occur in the immediate vicinity of Canovas Creek today, but is found on Mount Taylor to the northeast and in the Mogollon Mountains to the south, as well as in the White Mountains of Arizona to the west (Findley et al. 1975; Hoffmeister 1986). The woodrat genus *Neotoma* is also rare at Canovas Creek, represented by a maxilla with an upper first molar (M1). Six species of *Neotoma* occur in the modern fauna of New Mexico, found in most habitats, from deserts to grasslands to mountains (Findley et al. 1975). A large rabbit tentatively identified as the jackrabbit genus *Lepus* is represented by fewer than 10 specimens from Canovas Creek. This species is considerably rarer at Canovas Creek than the smaller rabbit *Sylvilagus nuttallii*. Four species of *Lepus* occur in New Mexico today, the most common and widely distributed of which is the black-tailed jackrabbit *L. californicus*, the only species that occurs at present near the Canovas Creek site (Findley et al. 1975). The snowshoe hare *L. americanus* and white-tailed jackrabbit *L. townsendi* are restricted to the northernmost part of the state, and the white-sided jackrabbit *L. callotis* is a rare inhabitant of the Chihuahuan Desert in southwestern New Mexico.

Canovas Creek is one of the highest Pleistocene sites in New Mexico, at an elevation just 10 feet shy of 8,000 ft (2,375 m). The only higher sites in the state are San Antonio Mountain (SAM) Cave at almost 9,000 ft (2,737 m), located a few miles south of the Colorado border in Rio Arriba County, and Tree Spring at 8,350 ft (2,545 m) in the Sandia Mountains east of Albuquerque in Bernalillo County. SAM Cave contains a medial Pleistocene (Irvingtonian NALMA) fauna consisting almost entirely of small vertebrates (Rogers et al. 2000). The only fossil known from Tree Spring is the American mastodon *Mammuthus americanus* (Lucas 1987; Lucas and Morgan 1997). Canovas Creek is the only high-elevation Pleistocene site from New Mexico that samples a diverse assemblage of both large and small mammals, thereby providing a previously unknown glimpse of the Rancho-labrean mammalian fauna from montane regions of the state. The vast majority of the more than 200 Pleistocene vertebrate sites in New Mexico, including open sites like Canovas Creek as well as caves, range from 1,000 to 2,000 m (3,500 to 6,500 ft) in elevation, with most sites well below 2,000 m. Canovas Creek represents the highest-elevation records in New Mexico for all five of the large mammals identified from the site, *Equus conversidens*, *E. occidentalis*, *Camelops hesternus*, *Stockoceros*, and *Mammuthus columbi*.

Small mammals often have specific habitat requirements and restricted home ranges, and thus tend to be more sensitive ecological indicators than large mammals, which are generally found over much larger areas and in a wider variety of habitats. Factors closely tied to elevation, such as precipitation and vegetation type, also tend to have a stronger effect on small mammals. Most of the small mammals identified

from the Canovas Creek fauna are indicative of montane habitats above 2,400 m (about 8,000 ft) in New Mexico, including *Sorex*, *Tamiasciurus hudsonicus*, *Thomomys talpoides*, *Microtus*, and *Sylvilagus nuttallii*, none of which occur today in the immediate vicinity of Canovas Creek (Findley et al. 1975). Because of the overall cooler temperatures and higher precipitation during the late Pleistocene, vegetation zones in New Mexico and the southwestern United States were displaced from 600 to 1,200 m (2,000 to 4,000 ft) lower than the elevation ranges in which similar vegetation zones are located at present (Dick-Peddie 1993). This phenomenon of the displacement of vegetative zones downward in elevation during the Pleistocene, and in some cases extending considerably farther south in latitude, has been widely recognized in New Mexico and elsewhere in the Southwest, both through the study of pollen (Hall 2005) and pollen and plant remains preserved in packrat middens (Betancourt et al. 2001). These vegetative changes, which indicate cooler temperatures and higher precipitation during the Quaternary Ice Age, are also reflected in the occurrence of many species of small mammals in late Pleistocene sites, particularly cave deposits, at lower elevations and farther south than their current distribution (Findley et al. 1975; Harris 1993). These changes in small-mammal distributions during the late Pleistocene led to many examples of what are called “non-analog” or “disharmonious” faunas, in which certain sites record the co-occurrence of species that are not found together at the present time. A significant number of non-analog faunas are recorded in late Pleistocene cave deposits in southern New Mexico, including Dry Cave in Eddy County, Pendejo Cave in Otero County, and U-Bar Cave in Hidalgo County (Harris 1985, 1993, 2013). Examples of mammals no longer found in southern New Mexico but present in one or more of these cave faunas, as well as Canovas Creek, include *Thomomys talpoides* and *Sylvilagus nuttallii*.

Additional Pleistocene Sites from the Gila Region

There are several other published Pleistocene vertebrate sites from the Gila Region in southwestern New Mexico. Most of these sites were reported by other paleontologists, and therefore the following discussion is based primarily on the literature. In addition to open sites, there are also three caves in the Gila Region that have produced late Pleistocene vertebrate faunas, Doolittle Cave and Howell's Ridge Cave in southern Grant County and Palomas Creek Cave near Hermosa in the Gila National Forest in western Sierra County. These caves are located east of the Continental Divide and thus outside the drainage of the Gila River and its main tributaries, which are the primary focus of this report. Harris (1985, 1993, 2013) provided faunal lists and other information for these caves, which are briefly mentioned in the Discussion.

Geologist J. C. Ratté collected Pleistocene fossils in 1977 on the north side of Shelton Canyon, about 2 km south-east of Glenwood in the Gila National Forest. The sample

includes more than 100 fossils collected over an area about 10 m wide and within 15 to 25 cm of the surface. The bulk of the collection consists of postcranial elements and a single cranial fragment of the peccary *Platygonus*, possibly from one individual, as well as an edentulous skull fragment of a very large horse (*Equus* sp.), a proximal phalanx of a smaller horse (*Equus* sp.), and a partial mandible of an antilocaprid. This site is probably Pleistocene in age, but lacks age-diagnostic species of mammals that would permit placement within one of the three Pleistocene NALMAs (Blancan, Irvingtonian, Rancholabrean). Leopoldt (1981) first mentioned fossils from this site, later named the Shelton Canyon LF (Morgan and Lucas 2005). The fossils from Shelton Canyon are housed in the USGS collection in Denver.

Leopoldt (1981) and Tedford (1981) discussed a mammoth found by Ana and Japh Howards about 1980 on the west side of the San Francisco River, 6 km south of Glenwood. The mammoth was derived from a brown, silty clay deposit in a terrace about 25 to 30 m above the river level. The mammoth fossils include a lower third molar (m3) and a partial tusk about 1 m in length. Based on the thickness of the enamel plates on the m3, Earl Manning and Richard Tedford of the AMNH (written communication to Winfried Leopoldt) identified the mammoth as *Mammuthus imperator*, suggesting a possible Irvingtonian age. The current location of the mammoth specimens is unknown, although some of the fossils were covered and reburied (Leopoldt 1981). Morgan and Lucas (2005) called this the San Francisco River site and considered it to be Irvingtonian.

Wolberg (1980) reported a skull of the small one-toed horse *Equus conversidens* from a roadcut exposure along Sapillo Creek, north of Lake Roberts in the Gila National Forest in Grant County. The skull was collected from Pleistocene stream terrace deposits in July 1979 by Donald Wolberg, John Hawley, and Jon Sandor. There are no published descriptions, measurements, or illustrations of this specimen. The horse skull from the Sapillo Creek site was deposited in the NMB-GMR collection in Socorro, New Mexico, but could not be found when this collection was transferred to the NMNH in 1994.

Discussion

Although this discussion is primarily concerned with Late Cenozoic (Neogene) vertebrate faunas from the Gila Region, there are also several records of Early Cenozoic (Paleogene) mammals from this area. Because of the extensive Eocene and Oligocene volcanism in the Gila Region, the vertebrate record from the Early Cenozoic is very incomplete and represented by only a few specimens. A lower jaw of the late Eocene (Duchesnean NALMA, about 40–37 Ma) brontothere *Duchesneodus uintensis*, a primitive odd-toed ungulate or perissodactyl superficially resembling a rhinoceros, was found in the Rubio Peak Formation along Turkey Creek northeast of Winston in the northern Black Range, western Sierra County (Morgan and Lucas 2012). Lucas (1986) reported a slighter younger latest Eocene fauna (Chadronian NALMA, about

37–35 Ma) from higher in the Rubio Peak Formation in the same general area, including a brontothere, the oromerycid artiodactyl *Montanatylopus matthewi*, a possible hypertragulid artiodactyl, and the rodent *Jaywilsonomys ojinagaensis*. Morgan and Lucas (2003b) identified two species of primitive artiodactyls called oreodonts, *Desmatochoerus* cf. *D. megalodon* and *Megoreodon* cf. *M. grandis*, from volcanoclastic sediments in the vicinity of Seventyfour Draw in the Taylor Creek drainage, just west of the Continental Divide, northwestern Sierra County. A late Oligocene age (early Arikarean NALMA, 28–26 Ma) is suggested by the biostratigraphy of the oreodonts from the Seventyfour Draw site (Morgan and Lucas 2003b) together with radioisotopic dates of 28.2 Ma and 26.1 Ma on volcanic rocks underlying and overlying, respectively, the strata containing the oreodonts (McIntosh et al. 1991).

Late Cenozoic fossil sites from the Gila Region provide a well-documented series of faunal assemblages that record major changes in the vertebrate fauna of southwestern New Mexico over the past 6 million years. The five major Gila sites described in this report provide a fairly comprehensive evolutionary history of this fauna, although there are some gaps in the record that can be filled with faunas from other parts of New Mexico or southeastern Arizona, corresponding to ages not currently represented in the Gila Region of southwestern New Mexico. The Late Cenozoic record of the Gila begins in the latest Miocene (latest Hemphillian NALMA) with faunas from Gila Group strata in the Mangas basin, the Glenwood Fauna in southern Catron County and the Walnut Canyon Fauna in northern Grant County. Latest Hemphillian (5.9–4.9 Ma) and somewhat younger early Blancan (4.9–3.0 Ma) faunas are readily distinguished by striking changes that occurred in the North American mammalian fauna in the latest Miocene and earliest Pliocene, probably associated with overall climatic deterioration characterized by cooler and drier conditions and related changes in vegetation. Comparison of the mammalian faunas between the latest Hemphillian Glenwood and Walnut Canyon faunas (see Table 1) and the early Blancan Buckhorn Fauna (see Table 2) reveals no overlap, documenting a major extinction event at the end of the Hemphillian (Tedford et al. 2004). Not a single genus (or species) is shared between the late Hemphillian and early Blancan faunas in the Mangas basin, even though they were collected from the same general area and are separated in time by less than 2 million years and perhaps as little as 1 million years.

Most of the genera identified from the Glenwood and Walnut Canyon faunas became extinct at the end of the Hemphillian. All members of the rhinoceros family (Rhinocerotidae), including *Teleoceras* from the Glenwood Fauna, disappeared from North America in the latest Hemphillian. In fact, the extinction of rhinos on this continent is one of the defining features for the end of the Hemphillian NALMA. The three genera of horses from Glenwood and Walnut Canyon, *Astrohippus*, *Dinohippus*, and *Neohippus*, all disappeared from New Mexico in the late Hemphillian, although *Dinohippus* survived into the earliest Blancan elsewhere in North America. The camels from Walnut Canyon, *Alforjas*,

Megatylopus, and *Pleiolama*, are unknown from New Mexico Blancan faunas. The Cervidae first arrived in North America from the Old World in the latest Miocene or earliest Pliocene, including the extinct genus of deer *Eocoileus* from Walnut Canyon, a genus known only from latest Hemphillian faunas (Webb 2000). Members of the deer family are a prominent component of the New World mammalian fauna throughout the remainder of the Pliocene and Pleistocene and into the modern era. The extinct species of fox *Cerdocyon texanus* and the extinct peccary *Catagonus brachydontus* from Walnut Canyon both belong to genera that survive today in South America, but disappeared from North America in the early Pliocene. *Cerdocyon* and *Catagonus*, together with the Walnut Canyon bear *Plionarctos*, an extinct genus related to the extant South American spectacled bear *Tremarctos*, were involved in the Great American Biotic Interchange, dispersing to South America in the late Pliocene or early Pleistocene between 2 and 3 Ma.

As recorded in Late Cenozoic faunas in the Gila Region, there was a nearly complete turnover of the mammalian fauna in New Mexico and western North America during the early Pliocene about 5 Ma, documenting the transition from the Hemphillian to the Blancan NALMAs. Most of the mammals that typify the Blancan NALMA were new to North America, either arriving by immigration from the Old World across the Bering land bridge or evolving in situ. Many genera of large mammals that first appeared in the Blancan survived throughout the remainder of the Pliocene and Pleistocene, only to disappear during the major extinction event at the end of the Pleistocene, discussed in more detail below. There are also a few genera of mammals that are present in both the late Miocene and the Pliocene, having survived the late Hemphillian extinction. All of these late Miocene holdovers became extinct in the Blancan, several of them managing to persist into the early Pleistocene (latest Blancan, about 2 Ma).

There are three Blancan (Pliocene and early Pleistocene) faunas from the Gila Region: from Grant County, the early Blancan (early Pliocene) Buckhorn Fauna; and from Hidalgo County, the late Blancan (late Pliocene) Pearson Mesa Fauna and the latest Blancan (early Pleistocene) Virden Fauna. These three faunas share many genera but few species, primarily a reflection of evolutionary change within generic lineages. Genera of mammals that first appeared in the Gila Region during the Blancan and survived until the end of the Pleistocene include the mylodont ground sloth *Paramylodon*, the one-toed horse *Equus*, the peccary *Platygonus*, the llama-like camels *Camelops* and *Hemiauchenia*, and the pronghorn *Capromeryx*. *Equus* is one of the most characteristic genera first known from the early Blancan, apparently derived from *Dinohippus* in the earliest Blancan. Several dozen species of *Equus* have been described from Pliocene and Pleistocene faunas in North America (Kurtén and Anderson 1980); however, the taxonomy of this genus is currently in a state of flux and the actual number of species is probably fewer than 10. *Equus* became extinct in the New World at the end of the Pleistocene, although several species in this genus still survive in Africa and Asia (zebras and donkeys). The large

extinct species *Equus simplicidens*, thought to be related to zebras, is known from Buckhorn and Pearson Mesa, but went extinct at the end of the Pliocene at about 2.6 Ma and thus is not present in the early Pleistocene Virden Fauna (Morgan et al. 1997, 2008). Three other species of *Equus*, *E. calobatus*, *E. cummingsii*, and *E. scotti*, first appeared in New Mexico during the late Pliocene (late early Blancan; between 3.6 and 3.0 Ma). These three horses occur in Pearson Mesa but not Buckhorn, and *E. scotti* is also known from Virden. *E. calobatus* and *E. scotti* are large horses, the former with elongated metapodials and the latter with short, stocky metapodials. *E. cummingsii* is a small species of *Equus* that went extinct about the same time as *E. simplicidens* at the end of the Pliocene, whereas *E. calobatus* and *E. scotti* survived into the early Pleistocene Irvingtonian NALMA (Kurtén and Anderson 1980). Tedford (1981) and Galusha et al. (1984) remarked on the increase in *Equus* diversity in the southwestern United States during the “medial Blancan” (= late early Blancan) around 3 Ma. The New Mexico record suggests this increase in *Equus* species actually began somewhat earlier than 3 Ma, but must have occurred after the deposition of the Buckhorn Fauna, in which only *E. simplicidens* is known.

The second genus of horse from the Blancan of New Mexico is *Nannippus*, one of the late Miocene holdovers that survived the late Hemphillian extinction. *Nannippus* is the last known member of the three-toed horse group or hipparionines that dominated North American equid faunas throughout the Miocene, surviving until the end of the Pliocene about 2.6 Ma. *Nannippus* is known from the late Miocene Clarendonian and Hemphillian NALMAs, as well as the Blancan (MacFadden 1984b). The species *Nannippus peninsulatus* is restricted to the Blancan, where it is known from both the Buckhorn and Pearson Mesa faunas, as well as five other early and late Blancan faunas (late Pliocene; ranging in age from about 3.6–2.6 Ma) in the Rio Grande Valley of New Mexico (Morgan et al. 2008). The absence of *Nannippus* from the latest Blancan Virden Fauna almost certainly documents the extinction of this genus, and the entire hipparionine group, sometime between 2.6 and 2.2 Ma.

All genera of artiodactyls or even-toed ungulates from the Gila Blancan sites are found in Blancan through Rancholabrean faunas but are unknown from the Hemphillian. Tedford (1981) reported the peccary *Platygonus* from the early Blancan Buckhorn Fauna, although the partial postcranial element from this fauna probably is not diagnostic at the generic level (Morgan et al. 1997). The large peccary *Platygonus bicalcaratus* is one of the more common species in the late Blancan Pearson Mesa Fauna. A partial skeleton of *Platygonus*, probably the species *P. compressus*, is known from the Pleistocene Shelton Canyon Fauna in Catron County. Two genera of camels occur in Blancan faunas in the Gila region, *Camelops* and *Hemiauchenia*, both of which are in the llama tribe Lamini. *Camelops* first appeared in the late early Blancan (about 3.5 Ma), and its occurrence in the Buckhorn Fauna may be one of the earliest records of this genus (Tedford 1981; Morgan et al. 1997). *Camelops* is found in most well-sampled late Blancan, Irvingtonian, and Rancholabrean

faunas in New Mexico. The giant llama *Camelops hesternus* is represented by several individuals in the late Pleistocene Canovas Creek Fauna. The long-limbed llama *Hemiauchenia* has been reported previously from late Hemphillian faunas, but Webb and Meachen (2004) referred most of these Hemphillian records (e.g., *H. vera*) to their new genus *Pleiolama*. As now understood, *Hemiauchenia* first appears in the early Blancan and is the most common camel in the Gila Blancan faunas. The large species *H. blancoensis* occurs at Buckhorn and Pearson Mesa, while the small species *H. gracilis* from Virden is restricted to latest Blancan faunas (Meachen 2005). A third species of *Hemiauchenia* of intermediate size, perhaps an undescribed species, is represented by a partial skeleton from Pearson Mesa. The dwarf pronghorn *Capromeryx*, characterized by a pair of straight vertical horns on either side of the head, first appears in the early Blancan and became extinct at the end of the Pleistocene. Evolutionary trends for *Capromeryx* in progressively younger sites are toward smaller overall size and reduction of the anterior of the two horns (White and Morgan 2011). The larger species *C. arizonensis* occurs in the late Blancan Pearson Mesa Fauna, while the smaller *C. furcifer* is known from late Pleistocene faunas, including Doolittle Cave in the Gila Region. All four genera of artiodactyls from the Gila Blancan faunas, *Platygonus*, *Camelops*, *Hemiauchenia*, and *Capromeryx*, became extinct at the end of the Pleistocene.

One of the most important paleontological and biogeographic events documented in the Gila Region is the Great American Biotic Interchange (GABI), the Late Cenozoic interchange of faunas between North America and South America. The GABI or Interchange began in the late Miocene (about 9 Ma) with the arrival in North America of two genera of ground sloths of South American origin, apparently by overwater dispersal since the two continents were still separated in the Miocene by an oceanic water barrier called the Central American Seaway (Morgan 2008). One of these sloths, the megalonychid *Pliometanastes*, has been identified from a late Miocene (early Hemphillian) fauna in northern New Mexico (McDonald and Morgan 2011) but is not known from the Gila. North America and South America became connected at the Panamanian isthmus in the early Pliocene about 5 Ma and the primary pulse of the GABI began, with additional South American mammals arriving in the southwestern United States by about 3 Ma, including the glyptodont *Glyptotherium*, mylodont ground sloth *Paramylodon*, porcupine *Erethizon*, and capybara *Nechoerus*. *Glyptotherium* and *Paramylodon* occur in the Pearson Mesa Fauna and *Glyptotherium* is also known from Virden. *Erethizon* and *Nechoerus* are unknown from Blancan faunas in New Mexico, although both genera occur in late Blancan faunas in southeastern Arizona (Morgan and White 2005). The living porcupine *Erethizon dorsatum* occurs in several late Pleistocene cave faunas in southern New Mexico, and currently is a common forest dweller throughout much of the state. The arrival of South American immigrants is the defining character for late Blancan faunas in New Mexico and elsewhere in the Southwest. The presence of glyptodonts and/or a mylodont

sloth in the Pearson Mesa and Virden faunas confirms their late Blancan age (< 3 Ma), whereas the lack of Interchange mammals in the Buckhorn Fauna indicates an early Blancan age (> 3 Ma).

There is a substantial time gap, corresponding to the entire Irvingtonian NALMA (1.6–0.25 Ma), between the early Pleistocene Virden Fauna and the next-youngest well-sampled fossil site in the Gila Region, the late Pleistocene (Rancholabrean NALMA) Canovas Creek Fauna. The Irvingtonian is defined by the first appearance in North America of the mammoth *Mammuthus* and the vole *Microtus* (Bell et al. 2004). A mammoth identified as the Irvingtonian species *Mammuthus imperator* was found along the San Francisco River in Catron County, but this site did not contain any other species. Significant changes occurred in New Mexico vertebrate faunas in the early Pleistocene (early Irvingtonian). Several genera found in late Blancan and early Irvingtonian faunas in New Mexico, Arizona, and Texas disappear about 1 Ma, including the giant land tortoise *Hesperotestudo*, the giant shelled glyptodont *Glyptotherium*, and the gomphothere *Cuvieronius*. *Hesperotestudo* and *Glyptotherium* occur in the late Blancan Pearson Mesa and Virden faunas, whereas *Cuvieronius* is known from several early Irvingtonian faunas in the Mesilla basin in Doña Ana County in southernmost New Mexico (Lucas et al. 2000; Morgan et al. 2008). These three genera survived into the late Pleistocene in Florida, Mexico, and Central America, suggesting they were adapted to a warm, humid subtropical climate, but disappeared from the Southwest in the early Pleistocene with the onset of cooler and drier climatic conditions.

The late Pleistocene Canovas Creek site shares several genera of mammals with older Pliocene and early Pleistocene faunas in the Gila Region, including *Equus* and *Camelops*, and also has several species in common with the modern fauna, including the carnivores *Canis latrans* and *Lynx rufus*, the rodents *Tamiasciurus hudsonicus* and *Thomomys talpoides*, and the rabbit *Sylvilagus nuttallii*. Although the age of Canovas Creek is not clearly established, the presence of the advanced mammoth *Mammuthus columbi* and several species of extant mammals are indicative of late Pleistocene (Rancholabrean NALMA) faunas. The transition from the late Pleistocene mammalian fauna at Canovas Creek to the modern mammal fauna in the Gila Region occurred rather rapidly during the last several thousand years of the Pleistocene epoch, between about 13 and 10 ka. The most notable aspect of this faunal changeover was the extinction at the end of the Pleistocene of most species of large mammals, the so-called Pleistocene megafauna, including five species from Canovas Creek, *Equus conversidens*, *E. occidentalis*, *Camelops hesternus*, cf. *Stockoceros* sp., and *Mammuthus columbi*, as well as many other large mammals known from late Pleistocene sites elsewhere in New Mexico (e.g., two species of ground sloths, five species of large carnivores, tapir, peccary, mountain goat, two species of muskox-like bovids, and mastodon, among others).

The cause(s) of the late Pleistocene megafaunal extinctions have been debated for more than a century, and

there is still no consensus among Pleistocene paleontologists (Martin and Klein 1984; Koch and Barnosky 2006). The two major competing theories are climate change and human hunting (the "Human Overkill" hypothesis). The climate change hypothesis proposes that the extinction of the megafauna was caused by a major shift in climate and vegetational patterns that occurred at the end of the Pleistocene. The Gila Region and elsewhere in the Desert Southwest transformed in the late Pleistocene from a cooler and wetter climate with widespread forests and grasslands to the warmer arid climate of today with extensive desert vegetation, especially at lower elevations. The large mammals became extinct because they were unable to adapt to the rapidly changing climate. The Human Overkill hypothesis proposes that Paleoindians were the primary cause of the extinction through hunting of large mammals, particularly ungulates, whose disappearance precipitated the collapse of the large mammal community (Martin 2005). Paleoindians first appeared in North America in the latest Pleistocene (about 13 ka or perhaps slightly earlier) during the period of major climate change. Although considerable disagreement still exists, Koch and Barnosky (2006) suggested that a combination of human hunting and rapid climate change at the end of the Pleistocene resulted in the extinction of the megafauna in North America.

Unlike megafaunal mammals, very few species of small mammals (shrews, bats, rodents, rabbits, etc.) became extinct at the end of the Pleistocene in New Mexico or elsewhere in North America. Instead, climatic changes from the late Pleistocene to the Holocene caused major shifts in vegetational zones that resulted in significant modifications in the distribution of small mammals in Gila Region. Several species of small mammals from Canovas Creek and other late Pleistocene faunas in southern New Mexico are now restricted to montane habitats in the high mountain ranges of northern New Mexico (e.g., Jemez Mountains, Sangre de Cristo Mountains, San Juan Mountains; Findley et al. 1975). These small mammals not only occurred much farther south than their current ranges, but they are often found as fossils at much lower elevations than these species occupy at present. Small mammals from Canovas Creek now restricted to montane habitats include the red squirrel *Tamiasciurus hudsonicus*, the northern pocket gopher *Thomomys talpoides*, and the mountain cottontail *Sylvilagus nuttallii*, as well as shrews (*Sorex* sp.) and voles (*Microtus* sp.). Howell's Ridge Cave in southern Grant County in the southernmost part of the Gila Region contains late Pleistocene deposits with a considerably more diverse fauna of small mammals than Canovas Creek (Harris 2013). *Sylvilagus nuttallii* is also known from Howell's Ridge Cave, as are the bushy-tailed woodrat *Neotoma cinerea* and the white-tailed jackrabbit *Lepus townsendi*, currently restricted in New Mexico to higher elevations in the northern mountains, and the sagebrush vole *Lemmiscus curtatus*, now found in sagebrush habitats in states just to the north of New Mexico. The distribution of small mammals in New Mexico during the late Pleistocene reflects the changes in vegetational zones at this time, in which the cooler and wetter

conditions allowed plants characteristic of montane regions to survive much farther south and lower in elevation than the current arid climate would permit.

Future paleontological field work in the Gila will surely add to the diverse record of Late Cenozoic vertebrates currently known from this region. Exploration of the Miocene and Pliocene exposures of Gila Group rocks in the Mangas basin in southern Catron County, especially in the Gila National Forest, has barely "scratched the surface" of potential important fossil finds in this extensive and rugged area. Despite the fact that the first vertebrate fossil ever reported from the Gila was found in southern Catron County in the 1880s (Cope 1884), little paleontological work has been done in this area since. Recent fossil finds near Glenwood, including a proboscidean tusk, a tooth of a horse previously unknown from the late Miocene of New Mexico, and a partial skeleton of a giant marmot (G. McDonald and G. Morgan, unpublished data), suggest that many new fossil sites await discovery.

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The Mimbres Biodiversity Project in Grant County, New Mexico: The Effect of Environmental Education on Fifth-Grade Student Learning Outcomes

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Abstract

Science education and positive outdoor experiences shape how children interact with and understand the environment. Unfortunately, today's classrooms are typically far removed from the outdoors and often rely on bookwork to teach scientific concepts. This pedagogy has resulted in a generation of children who express concern for the environment but lack critical-thinking skills necessary to resolve environmental issues. The Mimbres Biodiversity Project incorporated hands-on, outdoor activities with classroom learning in three fifth-grade classrooms from two schools situated within the Mimbres River watershed in Grant County, New Mexico. This pilot project aimed to test the hypothesis that place-based learning opportunities enhance student understanding and awareness of the environment. Parametric and non-parametric statistical analyses were used to assess pre- and post-test-project scores within and among classrooms. Results indicated that place-based learning that incorporates data collection and analysis positively enhances student knowledge and attitudes toward the environment and provides an important foundation for the development of environmental literacy.

Key Words: K-12 education, experiential education, inquiry, environmental literacy

Introduction

Nationwide, science education in the public school system has perhaps taken a back seat. In 2009, this trend was especially notable in New Mexico, with only 21% of eighth graders scoring proficient in science, significantly lower than the national average (Institute of Education Sciences 2009). Science education is expected to promote environmental literacy among students, which means that they will possess the ability to use scientific knowledge and skills to understand and make decisions about the natural world and the changes made to it through human activities (National Science Board 2000; Environmental Literacy Council n.d.). Today's children may express concern for the environment, but they lack the critical-thinking and decision-making skills that are necessary to resolve environmental issues (McBeth and Volk 2010).

This is not surprising. In the fifth through eighth grades, students begin to develop abstract- and creative-thinking skills, including the ability to understand the interplay of environmental and human-social systems (North American

Association for Environmental Education 2010). In New Mexico, the state's grade five Science Standards and Benchmarks require that science learning incorporate information that enhances student understanding about science and its role in everyday life (New Mexico Public Education Department [NMPED] 2013). Through this curriculum, New Mexico's fifth-grade students are expected to do the following:

1. Understand the scientific process and be able to use math to understand scientific knowledge (Strand I, Benchmarks I and III)
2. Understand the interdependence of living things and their environment (Strand II, Benchmark I)
3. Understand Earth structure and the processes and interactions of Earth's systems (Strand II, Benchmark II)
4. Understand how scientific knowledge influences individuals and societies (Strand III, Benchmark I)

Unfortunately, this curriculum does not provide teachers any practical support integrating these complex environmental science topics into the classroom. Instruction typically originates from worksheets and books and remains on a level that does not support the integration of critical-thinking and decision-making skills. On the other hand, the North American Association for Environmental Education (NAAEE) Guidelines for Excellence (2009) have become recognized among educators as the keystone tool for developing environmental science pedagogies. Unlike New Mexico's Science Standards and Benchmarks, the NAAEE Guidelines incorporate science content across the curriculum (i.e., art, social studies, math, literature, science) and offer suggestions for ways in which to incorporate content learning and critical thinking in each subject area. The NAAEE Guidelines also enforce the use of the local environment, or place-based methods, to promote student achievement.

Place-based education has become widely accepted as an effective science-teaching tool (NAAEE 2009, 2010; McInerney et al. 2011; Seymoure et al. 2013; Smith 2013). This learner-centered approach provides students with opportunities to construct their own understanding through hands-on inquiry-based investigations. Learners are engaged in direct experiences within the local community and challenged to use higher-order thinking skills to solve problems, sharing their ideas and expertise through active learning (NAAEE 2009). Place-based education provides learners with a path for becoming active citizens and stewards of the environment in general and of their place of residency in particular (Wood-

house and Knapp 2000). Numerous studies have shown that well-designed place-based initiatives can boost students' engagement in school and significantly enhance their academic achievement (Athman and Monroe 2004; Louv 2005 and references therein; Sobel 2012).

In 2011, working with the Gila Conservation Education Center, we designed and implemented (2012) a pilot project in Grant County, New Mexico, which incorporated the New Mexico State Standards and Benchmarks and NAAEE Guidelines for Excellence (2009) to develop a sequential and experiential place-based learning opportunity for fifth-grade students in their local watershed. The project consisted of the administration of a pre- and post-test; a series of classroom activities; and two field studies, which included student data collection and analysis. Specifically, this project aimed to test the hypothesis that place-based learning opportunities enhance student understanding and awareness of the environment.

Methods

As outlined above, the NMPED Science Standards and Benchmarks emphasize developing a foundation of environmental literacy in the fifth grade. For this study, we built upon the NMPED curriculum by incorporating NAAEE guidelines into our curricular model. All fifth-grade classrooms from all eight public elementary schools situated within the local watershed (i.e., Mimbres River watershed, Grant County, New Mexico) were invited to participate in the pilot project. The project was announced to all fifth-grade teachers in the above eight schools, and the first three teachers that responded, regardless of school or classroom, were selected to take part in the pilot project.

A total of 52 students from the Silver and Cobre Consolidated School Districts participated in this project (Table 1). Two teachers from the Silver Consolidated School District represented two different fifth-grade classrooms from the same school (Harrison Schmitt Elementary). One of these teachers identified her students as traditional fifth-grade learners (hereafter referred to as "traditional") while the other identified her students as gifted learners (hereafter referred to as "gifted"). The third classroom represented students from the Cobre Consolidated School District (Central Elementary School). The Central Elementary teacher identified her students as special-needs learners (hereafter referred to as "special").

Prior to any classroom activity, a 10-question pre-project knowledge and attitude test was administered to assess students' basic understanding of and attitude toward the environment (Table 2). Following the test, we met with each teacher to familiarize her with the project and to establish a timeline for project implementation. For all subsequent activities, we met with each classroom individually. During the first classroom meeting, we introduced students to Jörg Müller's book *The Changing Countryside* (2006). This collection of nine paintings documents the transformation of a rural to an urban landscape through human activities over a 20-year period. Students were tasked to work as a team to organize the sequence of the paintings (Fig. 1). Upon completion of this task, we led an open discussion to focus students' attention on the impact of human activities on the landscape. Students collectively completed an activity sheet to further focus their awareness on the ways in which human endeavors can impact and transform habitats (Table 3). A second classroom session introduced students to the differences between a nature preserve and a national forest. During this visit, students were asked to build upon their knowledge to identify human activities that could impact the land and then to consider places that people collectively agree to preserve (Table 4). All students live in close proximity to the Gila National Forest, one of the largest National Forest systems in the United States (Fig. 2), and were generally aware of the many activities that were permissible on National Forest lands (e.g., cattle grazing, hunting, and timber harvest). However, students were less clear about human activities that were permissible within a nature preserve (i.e., The Nature Conservancy's Mimbres River Preserve).

In February 2012, we met with each classroom at The Nature Conservancy's (TNC) Mimbres River Preserve (32° 53.891'N, 107° 59.864'W; Fig. 2). The preserve represents a heritage ranch site encompassing 113 ha (279 ac) of semi-arid upland and riparian habitats, including approximately 3.21 km (2 mi) of the Mimbres River (Goldman, n. d.). Acquired by TNC and the State of New Mexico in 1995, the site reveals a rich history of human occupation through pre-European archaeological ruins, an intact 1880s-era barn, obsolete irrigation ditches, the foundation of a 1950s dwelling, rock fences, corrals, and abandoned farm machinery (Fig. 3). In addition, the Mimbres River Preserve provides habitat for several species of greatest conservation need, including the Chihuahuan chub (*Gila nigrescens*), Chiricahua leopard frog (*Rana chiricahuensis*), common black hawk (*Buteo gal-*

Table 1. Participating schools. A total of 52 students from the Silver and Cobre Consolidated School Districts from Grant County, New Mexico, participated.

School District	Elementary School	Classroom Type	# Students	Male	Female
Silver Consolidated	Harrison Schmitt	Traditional	20	9	11
Silver Consolidated	Harrison Schmitt	Gifted	22	16	6
Cobre Consolidated	Central	Special needs	10	7	3
TOTAL			52	32	20

lus anthracinus anthracinus), Rio Grande sucker (*Catostomus plebeius*), and viceroy butterfly (*Limenitis archippus*) (New Mexico Department of Game and Fish 2010).

During the field studies, students were asked to make observations and collect data in order to understand site

ecology and physiognomy. Students spent the first portion of the February visit becoming familiar with the preserve. Adult volunteers mirrored fifth graders as they explored the site, engaging in dialogue only when prompted by a student question or observation. Otherwise, students made discoveries without

Table 2. Pre- and post-test. This test was given to all students prior to any activity and following all outdoor and classroom components of the project.

Pre- and post-test knowledge and attitude questions

1. The place where an animal or plant lives is called its . . .
 - a. preserve.
 - b. habitat.
 - c. living room.
 - d. soil type.
2. When water flows, it goes . . .
 - a. uphill.
 - b. downhill.
 - c. both uphill and downhill.
3. Which of the following need water to live?
 - a. Animals
 - b. Plants
 - c. Both animals and plants
4. If you were standing in a river, where would you find the water flowing faster?
 - a. Close to the shore.
 - b. The middle of the river.
 - c. Water flows at the same rate in both places.
5. Riparian means . . .
 - a. ready to pick.
 - b. something that has rips or tears in it.
 - c. near a stream or river.
 - d. a scientific name for a wild animal.
6. When a kind of plant or animal disappears and no longer exists, it has become . . .
 - a. lost.
 - b. dead.
 - c. extinct.
 - d. endangered.
7. A nature preserve is . . .
 - a. a special place.
 - b. outside.
 - c. protected.
 - d. All of the above.
8. Which of the following activities would NOT disturb the land where they occur?
 - a. Drilling a well for water.
 - b. A fire.
 - c. Riding a horse.
 - d. Creating a garden.
 - e. All of these could disturb the land.
9. True or False. Plants and animals can live anywhere if they have enough food and water.
 - a. True
 - b. False
10. Do you think it is important for people to set aside special places for plants and animals to live?
 - a. Yes
 - b. No



Fig. 1. Students determining the order of nine paintings from Jörg Müller's book *The Changing Countryside* (2006). This collection of paintings documents the transformation of a rural to an urban landscape through human activities over a 20-year period. Students were tasked to work as a team to organize the sequence of the paintings.

Table 3. Sample student activity sheet 1. After students determined the order of the nine paintings from Müller's book, students collectively completed this activity sheet to further focus their awareness on the ways in which human endeavors can impact and transform habitats.

Name _____

The Changing Countryside

1. Guess the length of time that has passed between the first scene and the last. Check one below.

___ 2 years ___ 20 years ___ 200 years

2. In the early scenes, what sorts of jobs do you think people had? What sorts of things did the kids do for fun?

3. Compare the earlier scenes to the last scene. What activities do you think are no longer possible?

4. Compare the earlier scenes to the last scene. Are there any new work or play opportunities that are possible because of the changes?

5. Were there any places that were saved from change? We call a saved place a preserve.

6. Look at all the scenes and decide what things you think contributed the most to the changes.

Table 4. Sample student activity sheet 2. Activity sheet used to assist students in identifying human activities that could impact the land and places that people collectively agree to preserve.

<p>Name _____</p> <p style="text-align: center;">Looking for Preserves</p> <p>1. Think about your home. Is there anything in your home that you or your family thinks is important to preserve? List any of these things or places in this space.</p> <p>2. Think about your school. Is there any part of your school that you or other people think is important to preserve? List these too.</p> <p>3. How about the Town of Silver City? Do you remember any parts of the Town that are preserved? List some of these below.</p> <p>4. We live near the Gila National Forest, which looks like a giant preserve, but is different because it has many uses. All National Forests are managed by a government agency called the Forest Service. When the Forest Service began, it decided that National Forests must provide . . .</p> <ul style="list-style-type: none"> • wood for our future needs • water for our future needs <p>And, after a while the Forest Service decided that National Forests should also provide . . .</p> <ul style="list-style-type: none"> • recreational sites for people (hunting, hiking, camping and more) • grazing land for livestock (ranchers pay a fee for this) • places where wild plants and animals can live <p>How do you think the National Forest is different from a place that is a preserve just for wild plants and animals?</p>
--

adult intervention. Following the discovery period, students regrouped and collectively discussed their observations. Students were provided data sheets (Table 5) for use in recording abiotic and biotic site data, identifying and compiling a list of organisms they encountered and recording each habitat where an organism was observed (riparian, upland, or both). Students were also asked to draw a site map during their first visit (Fig. 4).

Next, classes broke into smaller groups to collect environmental data (wind speed, air and ground temperature, stream velocity, and relative humidity). Each student was given the opportunity to measure each environmental variable, with groups averaging individual results (Fig. 5). Finally, groups created a plot in either an upland or riparian habitat using a standard hula hoop (approximately 71 cm diameter). Each group documented the occurrences of plants and

animals found within their plot, assigning organisms to broad taxonomic groups rather than identifying organisms to the genus or species level. A second field study took place at the Mimbres River Preserve in April 2012, during which students repeated data-collection methods. Students collected environmental data (wind speed, air and ground temperature, stream velocity, and relative humidity), recorded observations of species and their associated habitats, and documented the occurrence of organisms found within hula-hoop plots.

In late April 2012, we collated student data into a summary sheet (Table 6) that was provided to each class during our final classroom visit. From these data, students tallied the number of individual animals that were observed in each of three general habitats (upland, riparian, or both) and then calculated the proportion of each species encountered in each habitat to complete a summary analysis (Figs. 6 and 7).

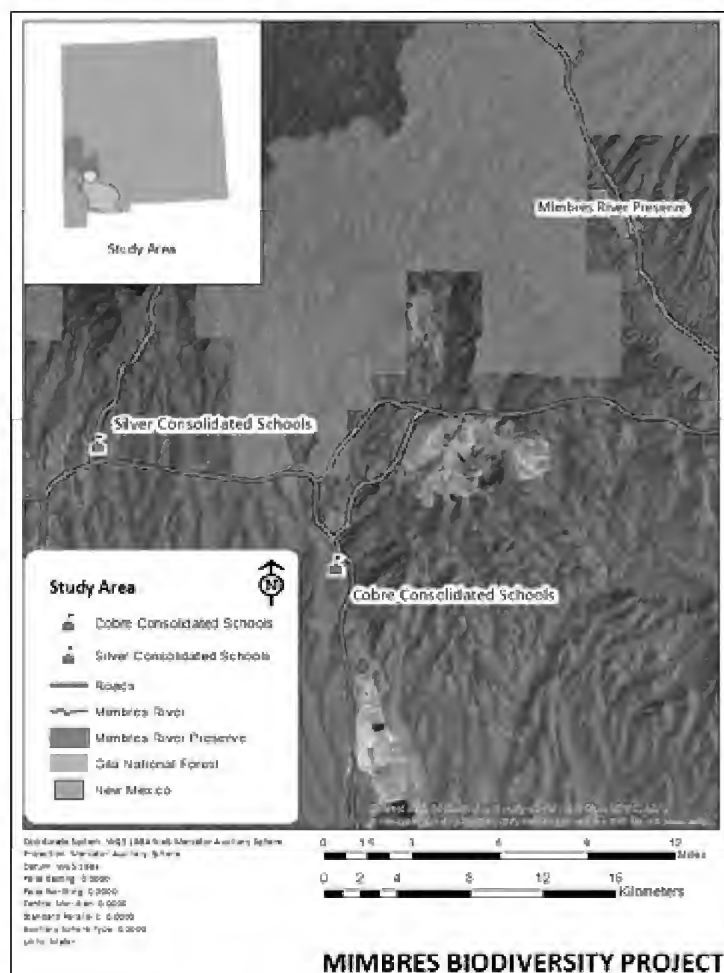


Fig. 2. Regional map. The Nature Conservancy's (TNC) Mimbres River Preserve represents a heritage ranch site encompassing 113 ha (279 ac) of semi-arid upland and riparian habitats, including approximately 3.21 km (2 miles) of the Mimbres River in Grant County, New Mexico.



Fig. 3. The Nature Conservancy's Mimbres River Preserve.

Following the final classroom visit, teachers administered a 10-question post-test (Table 2) to assess student knowledge of and attitudes toward the environment.

All students participated in all aspects of this project. Pre- and post-test scores were summarized by teacher classroom for all 10 questions (Table 7). Wilcoxon matched-pair tests were used to analyze for pre- and post-test differences. Analysis of variance on rank-transformed data was used to test for main and interaction effects of school, classroom (i.e., teacher), and sex on pre- and post-test scores (Conover and Iman 1981; SAS Institute 2008). All significant ANOVAs were followed by Tukey Honestly Significant Difference (HSD) post hoc tests to control for Type 1 error. All statistical analyses were conducted with JMP v. 10.1 (SAS Institute 2009) or SAS v. 9.1.3 (SAS Institute 2008).

Results

A total of 52 students were included in the data analysis. Pre-test scores indicated that knowledge and awareness within and among students, across all three classroom groups, was similar, $F_{3,48} = 1.4, p > 0.25$. There were no interactions between teacher and test score $F_{3,48} = 1.57, p > 0.21$ and male and female students performed similarly, $F_{3,48} = 0.25, p > 0.62$. On average, students correctly answered five

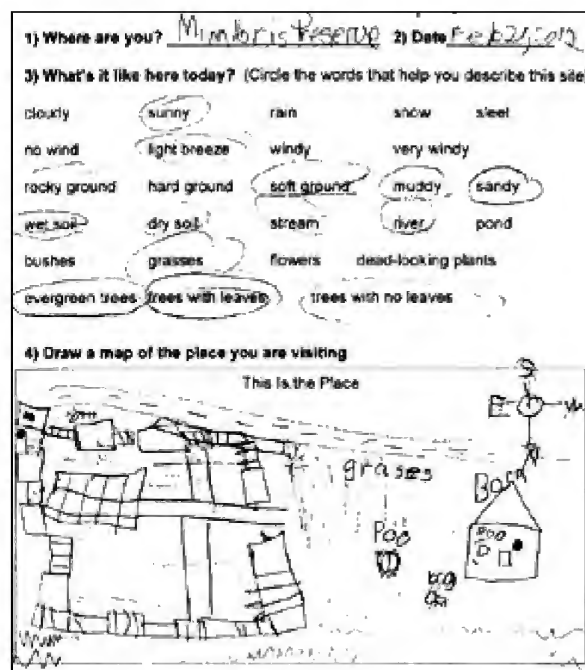


Fig. 4. Sample student site map. During each field trip, students collected data and described the abiotic conditions of the site. Students drew a site map during the first visit.

Table 5. Sample student data sheet. During each field trip, students collected data and described the abiotic conditions of the site.

Name _____ Teacher _____				
1) Where are you? _____ 2) Date _____				
3) What's it like here today? (Circle the words that help you describe this site)				
cloudy	sunny	rain	snow	sleet
no wind	light breeze	windy	very windy	
rocky ground	hard ground	soft ground	muddy	sandy
wet soil	dry soil	stream	river	pond
bushes	grasses	flowers	dead-looking plants	
evergreen trees	trees with leaves	trees with no leaves		
4) Draw a map of the place you are visiting				
<div style="border: 1px solid black; height: 300px; margin: 0 auto; width: 100%;"> <div style="text-align: center; padding-top: 10px;"> This Is the Place </div> </div>				
5) For the next four items, each team will measure one thing and report their findings to the class.				
Temperature _____ degrees Celsius—not Fahrenheit				
Humidity _____ percent (%)				
Wind _____ kilometers per hour (km/h)				
Stream Flow _____ meters per second ($\text{m}\cdot\text{s}^{-1}$)				

Table 5 (*cont'd*)

6) What do you see today? Ask a grownup to help you identify the things that you see.

Buildings or other man-made things _____

Birds/Bats _____

Animals with fur _____

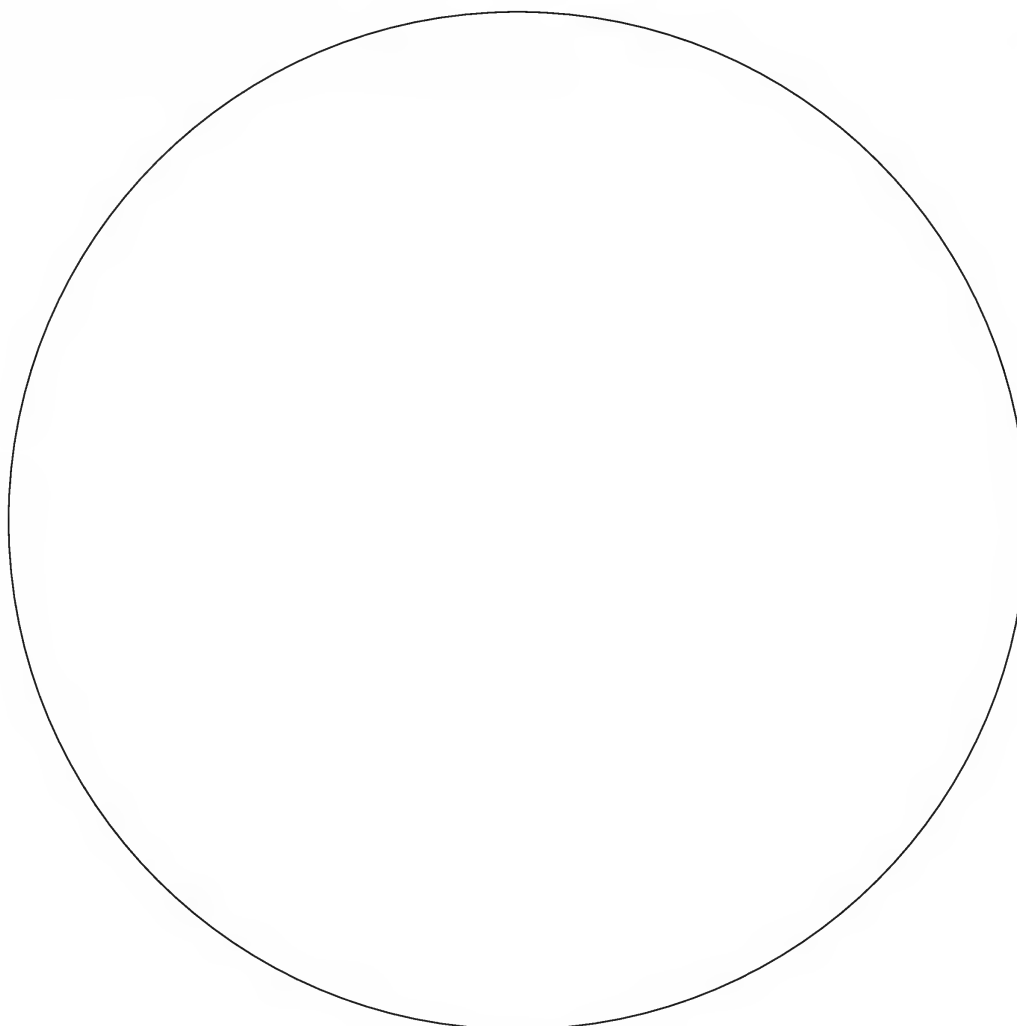
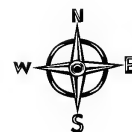
Reptiles/Snakes _____

Insects _____ Frogs or toads _____

Fish _____

Animal scat (poop) or tracks _____

MY HULA-HOOP CIRCLE



Each group will have a circle to explore. Look carefully inside your circle.
Mark the location of each thing you find. Then put a label next to each mark
to tell what you found.

Organism	Type (species)	Count	Habitat (R=riparian, U= upland, B= both riparian and upland)
Aquatic worms			
	leeches/aquatic worms	57	R
Snails			
	eggs	142	R
Arthropods			
	crafish	7	R
	ants	42	U
	spiders	5	B
	box elder beetle	25	B
	lubber grasshopper	3	U
	grasshopper	5	U
	sulphur butterfly	1	U
	monarch butterfly	2	U
	water strider	14	R
	stinkbug	2	U
	caddis fly larvae	70	R
	woods fly	2	U
	water penny (beetle)	3	R
	damsel fly	1	R
	may fly	1	R
	dragonfly	1	R
Fish			
	minnow	32	R
	eggs	28	R
Amphibians			
	unidentified frog	3	R
Reptiles			
	fence lizard	5	U
	whiptail lizard	7	U
Birds			
	towhee	2	U
	robin	5	B
	raven	3	B
	turkey vulture	3	U
	hummingbird	2	U
	red tailed hawk	1	U
	flycatcher	3	B
	swallow	1	R
	woodpecker	1	R
Mammals			
	deer (dead)	1	B
	coyote (scat)	1	B
	packrat	1	U
	fox (scat)	1	B
	bear (scat)	1	B
	elk (scat)	1	B
	people*	69	B

Table 6. Student data summary table. Each class was provided a summary of data collected by all students during each visit.

of nine knowledge questions correctly (questions 1–9; Table 2). In general, 88% of students were able to define *habitat* and understood that water generally flows downhill (questions 1 and 2; Table 2); however, all students had difficulty with the same four questions (questions 5, 7, 8, and 9; Table 2). The majority (75%) could not define the term *riparian* (question 5; Table 2); nor were they (76%) able to identify activities that could disturb the land (question 8; Table 2). Almost three-quarters (73%) were unable to define a nature preserve (question 7; Table 2), and most (69%) failed to recognize that plant and animal distributions are not solely dependent on food and water availability (question 9). Responses to the attitude question suggested students possess a positive attitude about the environment, with almost all students (87%) indicating that humans should set aside places for plants and animals to live (question 10; Table 2).

All classrooms performed significantly better on the post-test than the pre-test, $F_{1,48} = 22.88$, $p < 0.0001$ with no interaction between teacher and test results, $F_{2,48} = 2.76$, $p > 0.07$. All classrooms performed similarly on the post-test, $F_{3,48} = 1.57$, $p > 0.21$, with no interaction between teacher and test score, $F_{3,48} = 1.46$, $p > 0.24$. Analysis of variance on rank-transformed data indicated a significant within-subject interaction between pre- and post-test results and sex, $F_{3,48} = 4.47$, $p < 0.04$. Tukey post hoc comparisons of male and female students showed that male post-



Fig. 5. Data collection. Students established a hula-hoop plot and documented the occurrence of organisms found within these plots.

Fig. 6. Sample student analysis showing groups of animals encountered. All individuals were categorized into animal groups to create a bar graph. Students noted that insects were the most abundant group.

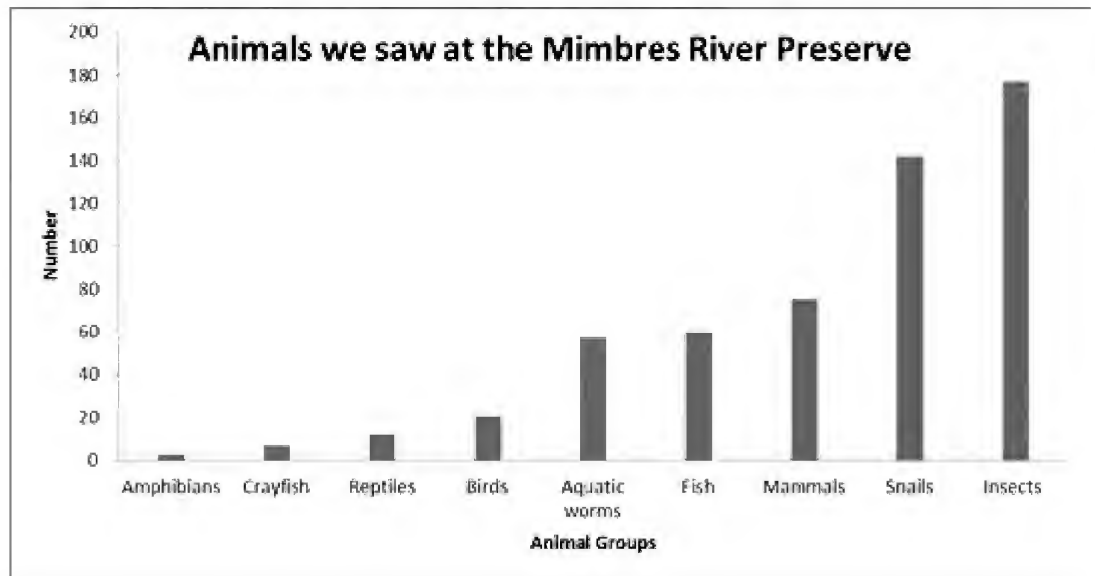
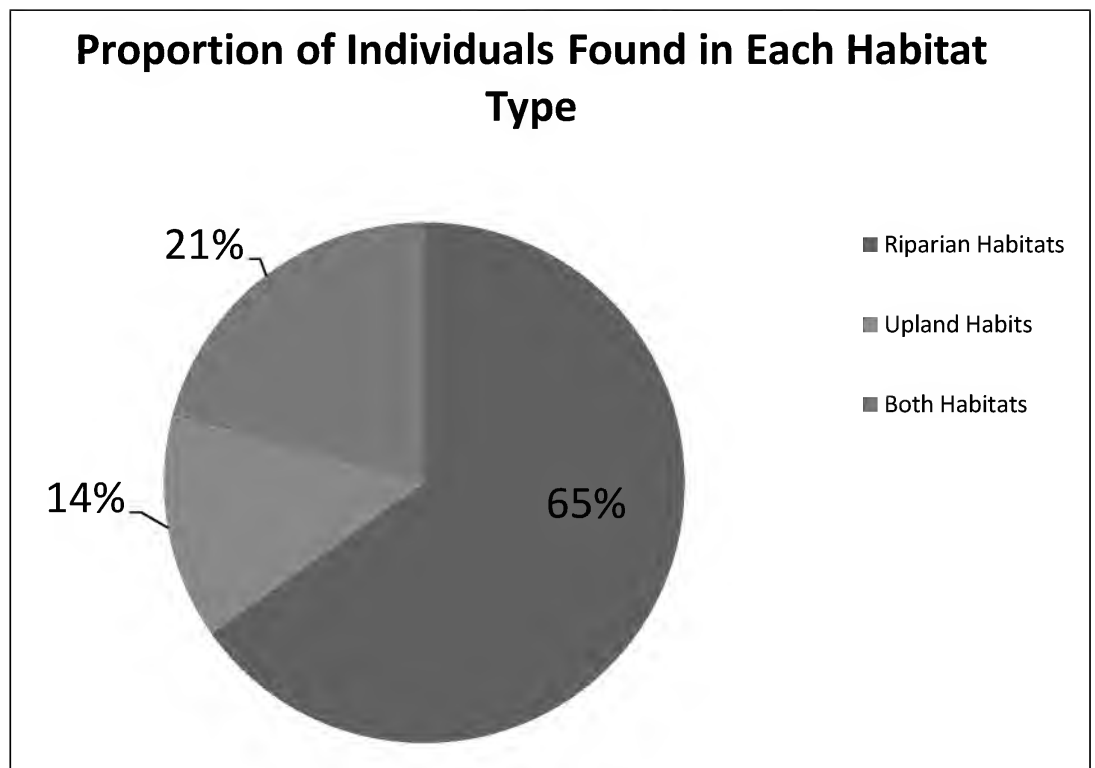


Fig. 7. Sample student analysis showing proportion of individuals found in each habitat. Fifth-grade students created a pie chart depicting the total number of individuals found in each habitat. Animals were more abundant in riparian habitats.



test scores improved by an average of almost two points ($= 1.59$, 95% CI [0.9–2.3]), while female scores showed only slight improvement ($= 0.6$, 95% CI [-0.14–1.34]). Central Elementary (special-needs classroom) improved test scores by almost three points ($= 2.5$, 95% CI [0.67–4.32]), but this result was not significantly different from Harrison Schmitt (gifted and traditional) classrooms, $F(1) = 2.91$, $p > 0.09$. Harrison Schmitt traditional classroom showed a one point improvement between pre- and post-test scores ($= 0.9$, 95% CI [0.2–1.6]), while the gifted classroom showed little overall improvement ($= 0.65$, 95% CI [0.0–1.5]).

Post-test scores for five questions (questions 2, 5, 6, 7, 8; Table 6) improved. On the post-test, 46% ($p < 0.01$) of students correctly identified activities that could disturb the land (question 8; Table 2). Similarly, more than half of all students (71%) were able to define a riparian area (question 5; Table 2; $p < 0.001$). Interestingly, post-test results indicate that students had a difficult time determining the general flow of water (i.e., downhill; question 2; Table 2; $p < 0.05$); all Central Elementary students indicated that water flowed both uphill and downhill.

Although results from this pilot study support the hypoth-

Table 7. Pre- and post-test scores. Repeated measures analysis of variance (MANOVA) indicate that all classrooms performed significantly better on the post-test than the pre-test, $F(1) = 22.88$, $p < 0.0001$.

	All Classrooms ($n = 52$)		Harrison Schmitt traditional ($n = 22$)		Harrison Schmitt gifted ($n = 20$)		Central special special ($n = 10$)	
	T ₁	T ₂	T ₁	T ₂	T ₁	T ₂	T ₁	T ₂
	\bar{X} (S.D.)							
	5.4 (1.32)	6.5*** (1.57)	5.4 (1.27)	6.3 (1.64)	5.8 (1.28)	6.45 (1.46)	4.8 (1.47)	7.3 (1.56)
Question	Percent Correct							
Q1	87	92	95	91	90	90	60	100
Q2	88	75*	95	86	85	100	80	0
Q3	98	100	100	100	95	100	100	100
Q4	69	79	64	73	75	85	70	80
Q5	25	71***	18	77	40	55	10	90
Q6	87	98*	86	95	95	100	70	100
Q7	27	54***	14	59	40	30	30	90
Q8	25	46**	27	32	25	45	20	80
Q9	31	46	41	32	35	40	40	90
Q10	77	87	74	91	80	75	80	100

* Significant differences at the 0.05 probability level

** Significant differences at the 0.01 probability level

*** Significant differences at the 0.001 probability level

esis that place-based initiatives enhance student understanding of the environment, student knowledge regarding biodiversity and its relationship to water did not change between pre- and post-test periods (question 9; Table 2). Following classroom and outdoor activities, almost half of all students (46%) still indicated that plants and animals could live anywhere if they had enough food and water.

Discussion

Prior to visiting The Nature Conservancy's Mimbres River Preserve, students participated in classroom activities to identify human actions that can affect the landscape. Students noted that as human populations increased, rural habitats were reduced, and in time were entirely absent from the landscape. Students recognized that plants and animals needed a place to live and asked questions about human activities as

they related to national forests and nature preserves. Through visits to TNC's Mimbres River Preserve, students began to consider how human activities impact habitats in their watershed and, through extension, how these activities impact organisms that are dependent on those habitats for survival.

Prior to this study, all classrooms and students demonstrated a similar level of environmental knowledge and awareness. The NMPED emphasizes ecosystem studies in the fifth grade, and most fifth graders were able to define a habitat and determine the general downhill flow of water. However, the majority of students could not identify activities that would disturb the land and most failed to recognize that plant and animal distributions are not solely determined by the availability of food and water. Overall, the majority of children demonstrated a positive attitude toward the environment before the project began. This finding supports McBeth and Volk's (2010) research showing that it is not uncommon

for children to express concern for the environment, even when they lack the critical-thinking skills necessary to resolve environmental issues.

The field trips provided students an opportunity to experience firsthand the long-lasting impacts of human endeavors in a rural setting. Seeing evidence of human habitation from the distant past conveys the idea that ecosystem sustainability should be a key societal goal (Sheppard et al. 2013). Students were intrigued by the old barn and associated farm infrastructure and identified these remains as habitats for some species. As they explored the upland and riparian areas associated with the preserve, students were quick to point out animal tracks and scat (i.e., black bear, *Ursus americanus*; elk, *Cervus canadensis*; and turkey, *Meleagris gallopavo merriami*) and to infer that those species were dependent on the particular habitat even though they were not observed. Distinguishing between observations and inferences can help students better understand how scientists use evidence to develop hypotheses and answer research questions.

Among other things, students documented the occurrence of box-elder beetles (*Boisea rubrolineata*), fish eggs, fish, crayfish (*Oronectes* sp.) and caddis fly larva (Trichoptera) in the riparian area (Fig. 8). In the more xeric upland habitats, students made note of harvester ants (*Pogonomyrmex occidentalis*); several common bird species, e.g., robin (*Turdus migratorius*) and raven (*Corvus*); whiptail lizard (*Cnemidophorus*) and fence lizard (*Sceloporus*); a deer carcass; and several tree species, including one-seeded juniper (*Juniperus monosperma*), alligator juniper (*J. deppeana*), and piñon pine (*Pinus edulis*) (Fig. 8). At least one student in each class was keen to note juniper seeds in scat and explain to his or her peers that juniper was a food source for some animals. Students recorded these observations on data sheets and, by doing so, gained an understanding of how and why scientists collect and record data.

After the field trips, classroom visits focused on the use of age-appropriate math skills to analyze scientific data (Strand I, Benchmark I and III; NMPED 2013). Students were provided with a data set that included the tally of all animals seen by all classrooms during each visit to the site (Table 6). From these data, students were tasked with creating a pie chart and bar graph (Figs. 7 and 6) to explain species distributions across habitats. Student graphs clearly illustrated that more species were found in riparian than upland habitats, and we facilitated a discussion to develop possible hypotheses to explain the observed pattern. Students drew on not only their data but also their personal experience in the different habitat types to hypothesize that more resources were available to plants and animals in cooler riparian habitats than in dry, upland habitats, and therefore, more species occurred in riparian habitats.

Upon completion of this pilot project, post-test results indicated a significant improvement in test scores across all classrooms. Interestingly, male scores improved by an average of almost two points over females. Place-based experiences are often transformative, particularly for those students who do not do well in traditional classroom settings. It could be

that the outdoors was more conducive to the boys' general learning style (Athman and Monroe 2004; Louv 2005; Sobel 2012; Sheppard et al. 2013). The most puzzling finding in this project was that the majority of students, after completing all components of this project, indicated that water flowed both up- and downhill (Table 2, question 2; Table 7). In the strictest sense, this is true, at least near the banks of the river where the downhill current forms eddies rotating counter to the direction of flow. Students could easily have observed leaves or sticks floating upstream along the river's edge during field studies and in turn interpreted the post-test question in the most literal sense. If true, this suggests that students were particularly engaged in the outdoors, with the experiences nurturing the development of deep understanding of a complex phenomenon (Sheppard et al. 2013).

Although results from this pilot study support the hypothesis that place-based initiatives enhance student understanding of the environment, student knowledge regarding biodiversity and its relationship to water did not change between pre- and post-test periods. Following classroom and outdoor activities, almost half of all students (46% vs. pre-test 25%) still indicated that plants and animals could live anywhere if they had enough food and water. Still, the relationship between water and biodiversity is a difficult concept to grasp (Seymour et al. 2013), and this pilot project laid important groundwork for students to draw upon as they continue to develop their understanding of ecological theory and their environmental literacy.

Conclusions

Most scientists who study the natural world can relate a pivotal childhood experience during which they fell in love with nature, and often they note an adult mentor who played a key role in the development of their curiosity (Coyle 2005; Sobel 2012). Experiences with nature can be transformative for young people, and positive youthful experiences in the outdoors have been cited as the single most important factor in promoting positive environmental behaviors in adults (Taner 1980).

The New Mexico Department of Game and Fish currently works with The Nature Conservancy to provide protection of riparian habitats associated with the Mimbres River in Grant County, New Mexico. Prior to this project, most students were unfamiliar with this site and the number of species that are dependent on its habitats. Following this project, students developed an increased awareness about their watershed, the Mimbres preserve, and the flora and fauna found there. Students also learned about the differences in allowable land-use practices on public land (i.e., the Gila National Forest), private land, and a preserve.

This project addressed needs for outdoor education that are typically unmet by the local schools. The Mimbres Biodiversity Project used existing community resources and gave students the opportunity to experience and learn about biodiversity and water resources through a simple scientific study. Students practiced using math and collected real data,



Fig. 8. Student observations at The Nature Conservancy's Mimbres River Preserve. From top left: (a) fish eggs, (b) caddisfly larva, (c) scat, (d) upland exploration, (e) deer carcass, (f) insect egg sacs.

Table 8. Teacher feedback. All teachers rated the pilot project favorably.

Teacher Feedback

How did the student experiences provided through this program align with your school's mandated curriculum? (Describe any changes you would make to increase its value to you as a teacher.)

Benchmarks were addressed for science.

It gave the opportunity for our students to experience science and math in the real world.

Were the experiences provided appropriate to your students' abilities? (Describe any changes you would make to increase its value to you as a teacher.)

Yes, the math was math formulas they were learning.

Yes.

Good but the math could have been more advanced.

Do you feel that the instructional strategies used helped your students develop critical-thinking skills and foster natural-resource stewardship? Can you provide any specific examples?

Our students learned how important our natural resources are and how quickly they can be gone.

Yes, measuring water flow.

Would you recommend this program to other fifth- grade teachers? (Describe any changes you would make to increase its value to you as a teacher.)

Absolutely, but not if I had to give up my space!!!

I highly recommend this program to other teachers. Anytime you can introduce your students to hands-on field work you have improved education with your students.

My students loved the exploring part of the field trip.

helping to raise awareness about the role that agencies and scientists play in the management and conservation of New Mexico wildlife and habitat. All teachers expressed enthusiastic support for the program, indicating that it reinforced science concepts and fostered development of math skills (Table 8).

Although pre- and post-tests showed that student knowledge did not change regarding an organism's relationship to habitat, this idea surfaced in wrap-up discussions both in the field and in the classroom. Such a complex idea requires multiple experiences for reinforcement, and this project laid the foundation for students to draw on their personal experiences as they encounter this concept in the future. Perhaps most importantly, this project documented a positive shift in attitude between pre- and post-survey results, with more students indicating after they had experienced the project activities that it is important for people to set aside special places for plants and animals to live. In all aspects, this pilot study supports the consensus of education research that students benefit from participating in real-world, place-based inquiry activities that enrich classroom concepts.

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Keynote

The Upper Gila Watershed through the Eyes of a Frog

Randy D. Jennings

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Starting in 1984, studies of the Chiricahua leopard frog, *Lithobates chiricahuensis*, in the Gila Region of southwestern New Mexico have provided a portal to understanding much about the frog and the Upper Gila Watershed. Distributed

broadly in aquatic habitats throughout the Gila, the Chiricahua leopard frog faces conservation challenges that mirror issues that have affected the Gila Watershed on a larger scale.

Session Abstracts

Promoting Ecological Literacy in the Changing K-12 Community

Stephanie Bestelmeyer, PhD

Asombro Institute for Science Education

Who will become the next ecologists, conservation biologists, and ecologically literate citizens? Considerable evidence from international and national comparisons shows that New Mexico students are not leaving high school with the skills, knowledge, and interest to fill these critical roles. As teachers work to improve students' science literacy, they are faced with numerous challenges, including increasing class sizes, high-stakes standardized testing in language arts and math, students who spend little time outside, few science resources, and limited support for field trips and other enriching experiences. As we work to overcome these challenges,

science education research is providing ample evidence on the strategies that work best for improving science literacy. In southern New Mexico, the nonprofit Asombro Institute for Science Education is putting these strategies into practice and providing hands-on, inquiry-based science education for more than 14,000 K-12 students annually. We will highlight several of Asombro's programs that help students understand the process of science, learn about the desert where they live, and consider ecology as a career option for themselves, often for the first time.

Benefits of Field Work with High School/Middle School Students along the Gila River of New Mexico and Arizona

Tiana Blackwater, Geneva Blackwater, and Jo Ellen Kinnamon

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A three-year documentary of projects that were done along the headwaters of the Gila River into Arizona. We discuss how this exploration benefited the students and parents, both

personally and educationally, and benefited the classroom teachers behind the scenes.

STEM in the Bureau of Land Management: Innovations for Natural Resources Education and Getting the Work Done

Jony Cockman, PhD¹, and Dave Henson²

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STEM in the Bureau of Land Management (BLM) is a program aimed at providing living laboratories for college, high school, and middle school students to increase their skills in STEM subject areas, learn about career choices in natural resource sciences, and assist the BLM in a portion of its inventory, assessment, and monitoring workload. Arizona BLM Safford Field Office has identified several programs that need additional workers and provide STEM opportuni-

ties. BLM biologists have joined with Eastern Arizona College and Eastern Arizona Science Initiative to develop a model program that reaches out to high school and middle school students, as well as to college students, who serve as mentors to the youth. The pilot program is in its second year and has overcome a number of obstacles, grown from lessons learned, and enjoyed successes that we would like to share with prospective STEM participants.

Surface Reclamation for the Hard Rock Mining Industry of Arizona and New Mexico: Challenges and Success Stories

Jony Cockman, PhD

Bureau of Land Management Safford Field Office

From Silver City to Tucson, mining companies face the challenge of reclaiming tens of thousands of acres in mine dumps and tailing. Hard rock mining accelerated under the provisions of the 1872 Mine Law to expand the economies of the western states and territories. It was not until 1993 and 1994 that New Mexico and Arizona, respectively, passed legislation to encourage the surface reclamation of mined properties. Hard rock mining in the Southwest is aptly named, since the

ore bodies are located in areas with little soil to utilize as cap material for revegetation. Best management practices for hard rock mining have come about much more slowly than the expansion of mine operations, and physical and political challenges have been created. An overview of the challenges and cutting-edge technology and innovations will be reviewed. This session is recommended for participants who plan to attend the mine reclamation field tour.

Finding a Lost Generation: A Personal Search for a Traditional Way of Life in the Valley of Baby Cottonwoods

Dale Dillon

Undergraduate student, Eastern Arizona College

My family and I have an ancestral connection to life along the San Carlos River, a tributary of the Gila. The San Carlos River in Apache is called Tiis zhazhe bi k'oh, meaning "the valley of baby cottonwood trees." Through my interviews with the people and my personal experience, I've come to the conclusion that the river has changed over the years and that a way of life is changing with it. Today the summer floods are few and the ice-cold runoff from the winter snows

seldom runs as in the past. Salt-cedar has invaded the valley. The values of our people have changed. I see it when they litter or cut mature cottonwood trees for branches to use in ceremonies. How do you address illegal dumping when most people can't afford trash-disposal service? These issues affect the habitat we have called home since establishment of the Reservation.

Gila Chub (*Gila intermedia*) Status and Conservation Measures in the Gila River Basin, New Mexico

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Although only a few historical records exist for Gila chub in New Mexico, it is known from Duck Creek, Turkey Creek, Mule Creek, and San Simon Cienega in the Gila River drainage and from headwaters and cienegas such as Apache Creek and Tularosa River in the San Francisco River drainage. The population in Turkey Creek is the only documented extant population of Gila chub in New Mexico. The New Mexico Department of Game and Fish developed and finalized a

recovery plan for this species in 2006, and the US Fish and Wildlife Service is currently developing a federal recovery plan. Conservation measures already implemented include active protection from the effects of the 2011 Miller Fire on the Turkey Creek population, surveys to find unknown extant populations and/or suitable habitat, and planning for repatriation of fish into suitable habitats.

Management of Southwestern Rangelands by Hypothesis: An Example from the Malpai Borderland Region

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The rangeland science profession in the United States has its roots in the widespread overgrazing and concurrent severe droughts of the late 19th century. Scientific activities to address these problems, and the resulting policies they influenced, were based on reductionist experimentation and productionist emphases on food and fiber. After a century of science and policy there are two perspectives that now shape our science. First, rangeland landscapes are extremely heterogeneous and provide a wide spectrum of goods and services; general principles derived from scientific experimentation must be contextualized to the distinct societal and

ecological characteristics of a location. Second, rangeland management occurs at spatial scales considerably larger than those that have been addressed in range science. Scaling up science results is not a simple, additive process. It requires applying the scientific method in a postmodern fashion where management is an integral part of hypotheses. Understanding a landscape's "genetic code" is central to this process. These points will be illustrated with an example of their application to rangelands in the Malpai Region of New Mexico and Arizona.

Strategic Design of Ranarium Facility Key to Successful Head-Starting of Threatened Frog Species

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The Chiricahua leopard frog (*Lithobates chiricahuensis*) was registered as a threatened species in 2002. Historically, this species' home habitat has included southeastern Arizona and western New Mexico within the tributaries and boundary of the Gila River drainage. Several contributing factors for its reduction in numbers and native habitat have been suggested, including predation by invasive species, loss of surface water in key geographic locations, and a fungal infection of chytridiomycosis. Eastern Arizona College has designed, constructed, and maintained a ranarium that has addressed these

factors while successfully head-starting Chiricahua leopard frogs (CLF) for reintroduction by Arizona Game and Fish into restored habitat within the Galiuros Mountains. This project has become an integral part of the Bio 295 curriculum, assisting and providing students with hands-on learning experiences in environmental and/or ecological professional careers. We believe this model to be applicable for educational institutions, ranchers, and family backyards for the promotion of the CLF management plan.

Prescribed Fire and Wildfire Effects in the Gila National Forest

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Prescribed fires and wildfires are used to manage fuels in fire-prone landscapes throughout the Southwest. These practices, however, typically occur under different conditions, potentially leading to differences in fire behavior and effects. The objectives of this study were to investigate the effects of recent prescribed fires, wildfires, and repeated fires in ponderosa pine forests. The Gila National Forest was the study area because it has a rich history of using fire as a restoration

tool. Fuels and stand structure were sampled using random plots stratified by fire severity. Surface and canopy fuels were similar between prescribed fires and low-severity wildfires. However, moderately severe wildfires significantly reduced basal area, resulting in lower loading of canopy fuels and crown-fire potential. Additionally, effects of wildfire on stand structure and fuels seem to be sustained in areas that burned in two or three wildfires in the past century.

Practicing Preservation Archaeology in the Upper Gila Region

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Since 2008, Archaeology Southwest (formerly known as the Center for Desert Archaeology) has conducted research at several late pre-contact (ca. AD 1200–1450) archaeological sites in the greater Upper Gila Region. We practice preservation archaeology, which combines a commitment to protect nonrenewable archaeological resources with a community-based research agenda. This paper focuses on our fieldwork in Mule Creek, New Mexico, where we have just completed

our second summer Preservation Archaeology Field School in collaboration with the University of Arizona. We highlight some of the challenges and rewards of our research program, which not only trains future archaeologists but also seeks to raise public awareness of the importance of the Upper Gila Region's archaeological resources. We also discuss our findings as they shed light on the issues of migration and identity formation in the late pre-contact Southwest.

The Gila as a Natural Landscape Experiment for Ponderosa Pine Forests

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Southwestern ponderosa pine forests evolved under a frequent surface-fire regime that created a mosaic of tree groups within a savanna matrix. Across the Southwest, however, most of these original forests have been significantly altered by logging, fire suppression, or both. The unique logging and fire-management history in the Gila National Forest provides a unique outdoor ecological laboratory where some of these forest structures and fire processes still operate. Over the past

several years we have initiated a series of ecological studies to determine the impact of managed fires on fuels, age structure, and tree spatial patterns both in and outside the Gila wilderness. Our results show that reintroducing fires to these fire-dependent forests has restored tree densities and spatial patterns to historical conditions. Hence these forests may be important qualitative and quantitative reference sites that can serve to guide restoration efforts across the Southwest.

Conservation of Amphibians and Reptiles in the Upper Gila Watershed

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Sensitive amphibians and reptiles within the Upper Gila Watershed of New Mexico suffer from habitat loss, as do most sensitive species throughout the world. The sources of that habitat loss are diverse. Among factors contributing to habitat loss or alteration are invasive, non-native species; catastrophic wildfire and fire-management practices; and potential habitat shifts associated with climate change. Currently recognized sensitive species found in the Upper Gila Watershed in-

clude three frog (*Lithobates chiricahuensis* Fed-T, *Lithobates yavapaiensis* NM-E, and *Anaxyrus microscaphus* NM-SGCN), one lizard (*Heloderma suspectum* NM-E), and two snake (*Thamnophis eques* NM-E, *Thamnophis rufipunctatus* NM-E) species. While future conservation efforts should address the needs of imperiled species, additional focal species and large-scale efforts (conservation preceding necessity) should provide a proactive complement to herpetological conservation.

Molecular Evolution of Vampires and Zombies: Are Parasitic Spider-Wasps (Hymenoptera: Pompilidae) and Their Host Spiders (Araneae) Engaged in an Arms Race?

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At WNMU we are studying the molecular interactions and evolutionary histories of host-parasite relationships between local spider-wasps (Hymenoptera: Pompilidae) and the spiders they capture and utilize as living food provisions for their own parasitic larvae. Approximately 90 species from 26 genera of pompilid wasps are known to occur in New Mexico. Some are host generalists and utilize a wide diversity of host spiders, while others are more specialized and target specific spider taxa such as tarantulas, wolf spiders, or orb weavers.

Pompilid wasp venoms contain short peptides that bind to a known site on spider voltage-gated sodium channels, resulting in paralysis (but not death) of the host. By using phylogenies, a diverse sample of species, and the sequencing of spider sodium channels and wasp venom peptides, we are testing the hypothesis that pompilid wasp venoms and host spider genes have co-evolved via an antagonistic selective process analogous to an evolutionary arms race.

The Ethnobotany of Wild Tomatillos, *Physalis* Species, in the Gila River Watershed and Greater Southwest

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The wild tomatillos, including the longleaf groundcherry, *Physalis longifolia* Nutt., and the New Mexico groundcherry, *P. subulata* Rydb., and closely related species found in the Southwest, have been an important wild-harvested food and medicinal plant group. I will discuss the traditional uses for food and medicine, and taxonomic difficulties. Subtle morphological differences recognized by taxonomists to distinguish these related taxa are confusing to botanists and ethnobotanists. The importance of wild *Physalis* species as food

is reported by many tribes of the region, including the Zuni and Apache, and its long history of use is evidenced by its frequent discovery in archaeological sites. These plants may have been cultivated by farmers from Pueblo and other tribes. The importance of this plant as medicine is highlighted by its ethnobotanical history of use and our Native Medicinal Plant Research Program's recent discovery of 14 new secondary compounds, some of which have potent anti-cancer activity.

The Effects of Sodium Perchlorate on *Daphnia magna*

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The Gila River is now diverted through the Gila River Indian Community through canals when water is sufficiently flowing. In 2005 the community won a major water treaty in Indian Country in the US. This has brought in Colorado River water and recharged water. Our research has found that the lower Colorado water has a measurable amount of sodium perchlorate (used in rocket fuel, matches, and military and NASA projects), which affects the metabolism and the pituitary gland (thyroid) in children and adults. One study shows that children are being affected through milk. We studied *Daphnia magna* due to its being a microscopic organism on

the first tier of the food chain. We collected 50 *Daphnia* and examined each one under a microscope. We timed the normal heartbeat and then added one drop of a solution of distilled water with 0.1% sodium perchlorate. We again counted the heartbeat. We observed an increase in the heartbeat from 136 to over 300 in many cases. After 15 minutes we took a third heartbeat count and found that it had dropped only 62% (to between 150 and 170). The reaction to the sodium perchlorate lingered on for another couple of hours. This year we begin our second phase of the study, in which we will be using different types of soils as a filter system.

Is High-Severity Fire a Natural Part of the Gila Wilderness?

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The 2012 Whitewater-Baldy Fire burned large areas in the Gila Wilderness with high burn severity. As in much of the West, the pine-dominated forests of the Gila historically burned frequently at low severity. This suggests that recent stand-replacing fire in this forest type is outside the historic range of variability. However, less is known about the natural role of fire in the high-elevation, wetter, mixed-conifer, aspen, and spruce-fir forests. I present tree ring-reconstructed fire-history data collected from the highest-elevation forests in

the Mogollon Mountains, within the burn perimeter of the Whitewater-Baldy Fire. The results indicate that high-severity fire was a natural component of these wetter forest types. The largest tree ring-reconstructed high-severity patch in the mixed-conifer-aspen forest was > 500 acres, with a minimum estimated total of 2,500 acres of high-severity fire within the study area. These data can be used to give a historical context to high-severity patch sizes that burned in upper-elevation forests during the 2012 Whitewater Baldy Fire.

Measuring Increased Watershed Hydrology Pre- and Post-Thinning Treatments

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The project measures watershed hydrology before and after mechanical thinning and prescribed burning in an upper and lower Ponderosa and pinyon-juniper watershed. The project is using a paired watershed approach given the available climate, soil moisture, alluvial groundwater, and domestic groundwater for three years prior to thinning. Existing biomass, groundcover, and canopy cover will be compared to soil moisture, evapotranspiration, alluvial and domestic groundwater response and retention to rainfall and snowfall events pre- and post-thinning. The project intends to measure increased watershed hydrology from thinning treatments,

take the available data/information, and share/educate the National Forest and public in an effort to prioritize future treatments that may yield additional water. The project aim concentrates on existing watershed condition that has the ability to shift toward a stable herbaceous fire-climax system. Prioritizing treatments based on geology, the potential to alter watershed vegetation, treatments that target well-developed soil profiles, soil water-retention properties, and presence of measurable base alluvial water can maximize cost/benefit thinning treatment alternatives.

Genetic Analysis Suggests High Conservation Value of Peripheral Populations of Chihuahua Chub (*Gila nigrescens*)

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Genetic drift is expected to be the predominant evolutionary force in small, fragmented peripheral populations, which can lead to divergent allele frequencies and lowered diversity compared to the core population. Peripheral populations are not considered a high priority for conservation for this reason. However, peripheral populations may possess unique genetic variability not found elsewhere in the species' range, and may be especially important if core populations are at extirpation risk. We characterized levels and patterns of genetic diversity for peripheral populations of Chihuahua chub in

New Mexico, and compared these results to populations in Mexico. New Mexico populations of Chihuahua chub were genetically depauperate, but harbored distinct variation compared to those in Mexico. All New Mexico populations were significantly divergent from one another, suggesting little genetic exchange. Chihuahua chub in New Mexico thus represent a unique component of the species' evolutionary legacy and have more legal protection than counterparts in Mexico, suggesting high conservation value of these peripheral populations.

Gene Flow and Habitat Connectivity in the Gila River: Which Native Fish Species Are Most Susceptible to Negative Effects of Habitat Fragmentation?

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Because the upper Gila River Basin is one of the last unpounded drainage basins in North America, it is a stronghold for a unique fish fauna; however, distributions of native fishes have declined. We used microsatellite DNA markers to examine population structure of five native species with varying life-history strategies. Opportunistic life-history strategists are spikedace and loach minnow (recently listed as endangered), and longfin dace. Periodic life-history species are desert sucker and Sonora sucker. We collected fin clips from species

at seven localities representing a 96 km longitudinal section of the Gila River of New Mexico. Opportunistic species had higher genetic diversity at upstream sites than downstream, whereas periodic species showed little change in genetic diversity. Our comparative genetic study shows that migration and persistence of opportunistic species will be most strongly affected by anthropogenic and natural factors that limit habitat connectivity in the Gila River.

Western Apache Natural World Projects

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The upland half of the Gila River flows entirely through traditional Apache country, and most of this is in the traditional Western Apache homeland. Traditionally Western Apaches left as light a footprint on the natural world as possible, and worked hard to live in an ecologically sustainable manner. Traditional Apache life is governed by a deep and sophisticated knowledge of the natural world and by use of this knowledge to maintain healthy relationships with all the

natural world's elements. For the past several years, the San Carlos Apache Tribe, White Mountain Apache Tribe, Tonto Apache Tribe, and the Apaches of the Yavapai-Apache Nation have worked jointly on a number of projects documenting traditional Apache knowledge of all of the elements—creatures, plants, places, atmospheric and geographic features, and other living things—of the natural world of this region and how to live properly and powerfully within it.

The Arizona Water Settlements Act and Activities Affecting the Gila River Basin

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The Arizona Water Settlements Act (AWSA) is a complex web of agreements affecting the laws and policies of federal, state, tribal, and local governmental agencies and water-management entities in Arizona and New Mexico. The AWSA reduces uncertainty for non-Indian municipal, industrial, and agricultural water users, assures tribes of long-term water supply, and provides assistance to build water infrastructure. Various sections of the AWSA modify repayment of the Cen-

tral Arizona Project (CAP), reallocate CAP water, authorize the Gila River Indian Community water rights settlement, and reauthorize and amend the Southern Arizona Water Rights Settlement Act of 1982. This presentation provides a brief background and overview of the AWSA components and parties to the settlements, and discusses Reclamation activities associated with implementation of several AWSA provisions in the Gila River Basin.

The Chiricahua Apache

Joe Saenz

This presentation will be a holistic perspective involving the natural, cultural, economic, and spiritual aspects of the

earth's connection and this homeland of a unique people and their contribution to the world.

The ISC Gila Planning Process

Craig Roepke

Deputy Director, Interstate Stream Commission

The Arizona Water Settlements Act (AWSA) was signed into law in December 2004. The AWSA provides New Mexico with up to an additional 14,000 acre-feet of water from the Gila Basin and up to \$128 million in non-reimbursable federal funding. Some see the AWSA as opportunity, some as a threat. The Commission's policy is to do its best to protect the environment, use the best science, and meet present and future water needs. In February 2012, the Commission

selected 16 of 45 stakeholder proposals for further study and assessment. By December 2014, after 2½ years of intensive legal, technical, ecologic, and economic investigations, and further public input, the AWSA requires the Commission to make its final selections. The 16 projects may be combined, integrated, or modified. They must protect and could even enhance the unique and valuable Gila ecology.

Gila Watershed Rapid Assessment Method for Riverine Wetland Condition

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Very little is known about the function or condition of wetlands in New Mexico, even though wetlands supply numerous ecological, economic, and cultural benefits to local communities—including water-quality protection, flood control, erosion control, fish and wildlife habitat, education, and recreation. The New Mexico Wetlands Program is developing a Wetlands Rapid Assessment method in order to classify, assess, and monitor New Mexico wetland resources. The most recent phase focuses on two subclasses of riverine wetlands in the Gila Watershed, the mid-montane riverine subclass and the lowland riverine subclass. Gila Watershed riverine wetlands are unique and critical ecological components of one of the few relatively intact watersheds in the arid

Southwest. The New Mexico Wetlands Rapid Assessment combines landscape assessment in a GIS platform and a set of observable field indicators to express the relative condition of a particular site. Data will be collected from two sets of sites—one for each subclass. Sites will be selected to reflect a disturbance gradient and will be scored based on their ecological condition. Without assessment information, wetlands resources will continue to decline from a variety of stressors. This information will inform ecosystem management aimed at minimizing loss and degradation, protecting wetland acreage, preserving critical ecological processes that are linked to wetland habitat, and maintaining wetland function.

Suggestions for Future Avian Investigations in the Gila River Valley of New Mexico

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The New Mexico Gila River Valley, from the border of Arizona to the headwaters of the West, Middle, and East forks, is known for its diverse avian fauna. Many species present along this Southwestern riparian corridor are little understood. This presentation will consist of a discussion of those

species that will benefit from a better understanding of their biology in the arid Southwest. Brief comments will be made about the state and federal threatened and endangered species that occupy these riparian habitats, as well as selected Neotropical migrants that breed in this area.

Balancing Act: Meeting Human and Environmental Needs under the AWSA

Allyson Siwik

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Stakeholders in southwest New Mexico are trying to determine how to use funding under a Congressional water bill to cost-effectively balance water supply and demand while at the same time protecting the Gila River. The Arizona Water Settlements Act provides the four counties in Southwest New Mexico (Grant, Luna, Hidalgo, and Catron counties) with the opportunity to use federal funding for water projects that meet a water-supply demand. These funds don't need to be

used on a large-scale water-diversion project. This presentation will discuss alternatives being considered in the AWSA planning process that can meet the region's water needs at low cost, providing affordable water to users, while at the same time maintaining the Gila's in-stream flows that provide critical ecosystem services and that are important to the area's tourism economy.

Interactions of Gila River Streamflow and Alluvial Groundwater in the Cliff-Gila Valley, New Mexico

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Major Gila River floods in the Cliff-Gila Valley interact with historic anthropogenic features, like those left by mid-20th-century river-channelization efforts, to modify the river's planform and create a complex network of abandoned channels across the broad floodplains. Where remnant channels diverge from the active channel, they often divert part of the river's flow during even small to moderate floods (ca. 1,000–2,500 cubic feet per second [cfs]), carrying surface flow across the floodplain far from the active channel. Smaller floods occur far more frequently than large ones; the USGS station *Gila near Gila* recorded 323 floods of 1,000–2,500 cfs during the 68 years 1929–1996, and only 23 floods of > 5,000 cfs during the same years. The capacity to retain alluvial

groundwater largely determines the resilience of riverine and wetland ecosystems in this drought-prone region, and smaller floods may therefore be important for sustaining such off-channel habitat. Thirteen valley-wide transects through the Cliff-Gila Valley were established and instrumented for long-term monitoring beginning in 2008; data collected annually include topography and vegetation and habitat types. Groundwater and surface stage data are recorded at 30-minute intervals. Preliminary evaluation shows that more valley riparian habitat is found off the active river channel than adjacent to it, and that alluvial groundwater levels rise rapidly during even small flood events.

Calibrating Our Progress toward Recovery of Amphibian Populations: An Area-Based Approach and Occupancy Modeling

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Like many amphibian species worldwide, the Chiricahua leopard frog (*Rana chiricahuensis*) experienced a dramatic, rangewide decline during the past three decades and was listed under the Endangered Species Act (ESA) as threatened in 2002. A species recovery plan was finalized in 2007 that included four recovery criteria that, when reached, will have

1. established sufficient populations and metapopulations,
2. managed the necessary aquatic breeding habitats,
3. managed important dispersal corridors, and
4. reduced threats so that the Chiricahua leopard frog no longer needs the protection of the ESA. Although great progress has been made since federal listing, progress on recovery criterion 1 has been hampered by

1. the dearth of suitably configured landscapes that could “host” candidate metapopulations, and
2. the difficulty of establishing and monitoring stable and viable metapopulations given the limited human and financial resources available.

I develop a conceptual area-based approach to calibrate progress toward recovery that is applicable to the Chiricahua leopard frog and that utilizes occupancy modeling to gauge progress in establishing, managing, and monitoring viable metapopulations. This approach is easier to design and implement, makes fewer assumptions, and is less biased than the current “strict metapopulation” approach, and is applicable to other patchily-distributed amphibians.

From Then to Now: How the Presence or Lack of Surface Water Has Affected the Birds and Wildlife in the San Simon Valley

Kyle Tate

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Historically, the San Simon Valley flourished, covered by grasses and supported by springs and wells. The San Simon River flowed perennially and a large number and variety of birds existed in this ecosystem. Most surface water has since vanished. The colorful fowl that once could be seen using this valley as a flyway during migratory seasons are observed in smaller numbers and in some cases are no longer observed. Now, several agencies are combining resources to identify

and restore riparian habitat in this valley, hoping for resurgence in bird populations. Through observation and research, the BLM, Rocky Mountain Bird Foundation, Eastern Arizona College, and Arizona Game and Fish are monitoring the habitat and fowl to see if restoration efforts such as the Howard Well, Posey Well, and Sands Draw projects are benefiting the area, with the objective of attracting a broader diversity of fowl back to the San Simon Drainage.

Two Sister Floras: Comparisons of the Vascular Plant Diversity in the Mountains of Southeastern Arizona and Southwestern New Mexico

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The Santa Catalina Mountains are situated in southeastern Arizona within the Madrean Sky Island Chain, located in Pima and Pinal counties. The study area is 124,812 ha (308,416 ac, or 481.6 mi²), with an elevation gradient from 762 m (2,500 ft) to 2,197 m (9,157 ft). Although only the 5th tallest range in southern Arizona, the Santa Catalinas possess the greatest currently known vascular plant diversity within the area. The flora contains 1,391 species (1,436 species and infraspecific taxa) of vascular plants, with Madrean, Sonoran,

Chihuahuan, and Rocky Mountain affinities. In contrast, the Gila National Forest area in southwestern New Mexico, with a similarly large elevation and vegetation gradient but an area roughly 10 times larger (1.4 million ha, or 3.5 million ac) contains about 1,650 species (documented in gilaflora.com and SEINet), or roughly only 10% more species. This presentation compares the floras of these two sister mountainous regions, highlighting key floristic similarities, contrasts, and threats.

Baseline Connectivity of Native and Non-Native Fishes in an Unfragmented Arid-Land Riverscape

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The biological integrity of rivers is compromised by their becoming increasingly fragmented and by the threat of introduced species. Fragmentation and introductions are especially problematic in arid-land systems, where native fishes have limited water resources. Assessing connectivity of fishes in remaining unfragmented rivers will help generate management goals for fragmented systems. To measure connectivity in an unfragmented arid-land river, we calculated colonization and extinction probabilities of fishes in the Gila River, New Mexico. Colonization and extinction were calculated

from presence/absence data collected three times seasonally across six sites during 2008–2011. Of the 8 native species we encountered, 7 had colonization that exceeded extinction; the other had approximately equal rates. For non-native fishes, colonization exceeded extinction for 7 of 12 species, whereas colonization was less than extinction for the other 5. These results suggest unfragmented systems may promote the connectivity of native fishes more than non-natives, reinforcing the importance of connectivity to conservation.